

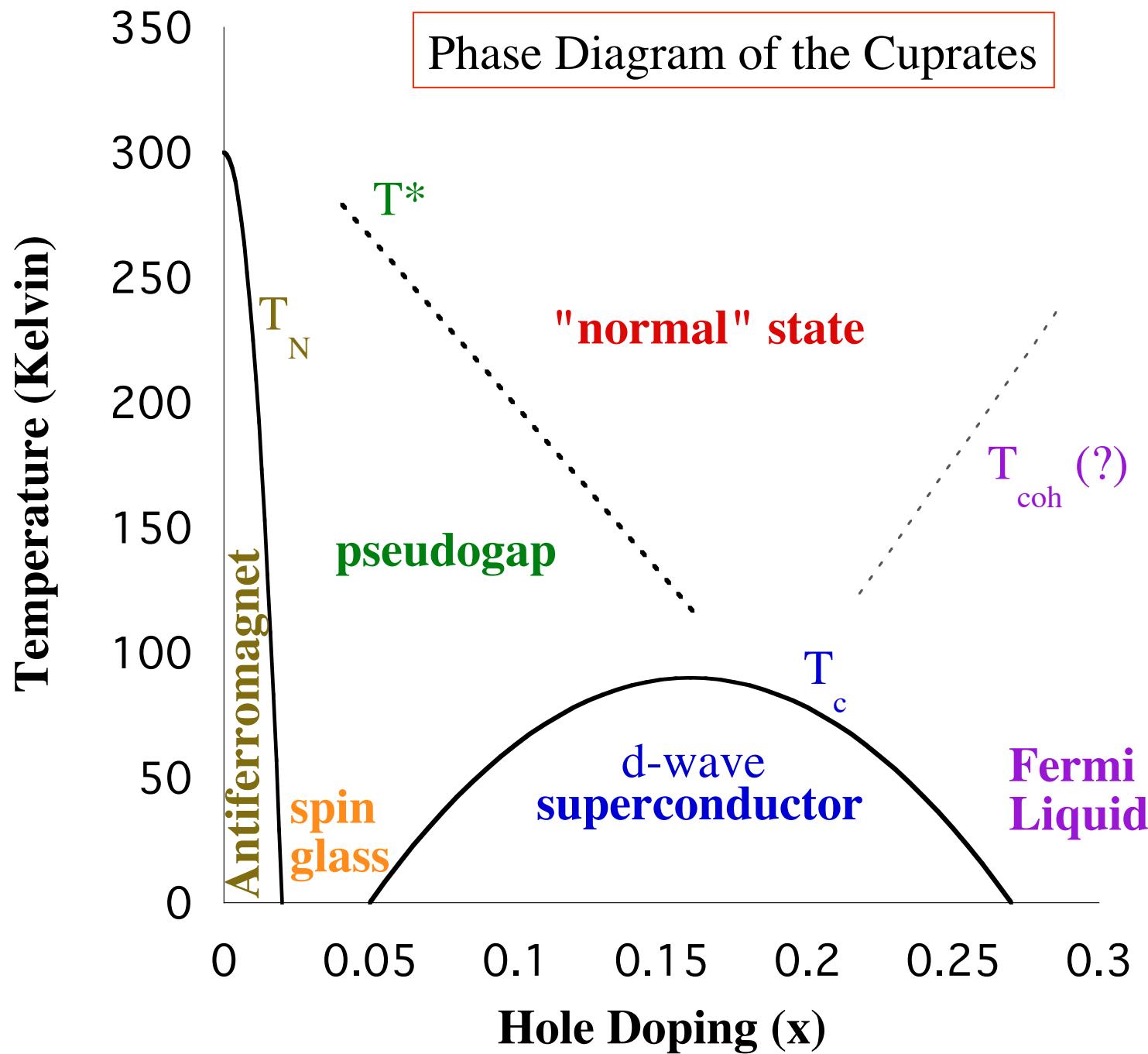
Is the Pseudogap a CDW Gap?

Mike Norman

Materials Science Division
Argonne National Laboratory
&
Center for Emergent Superconductivity



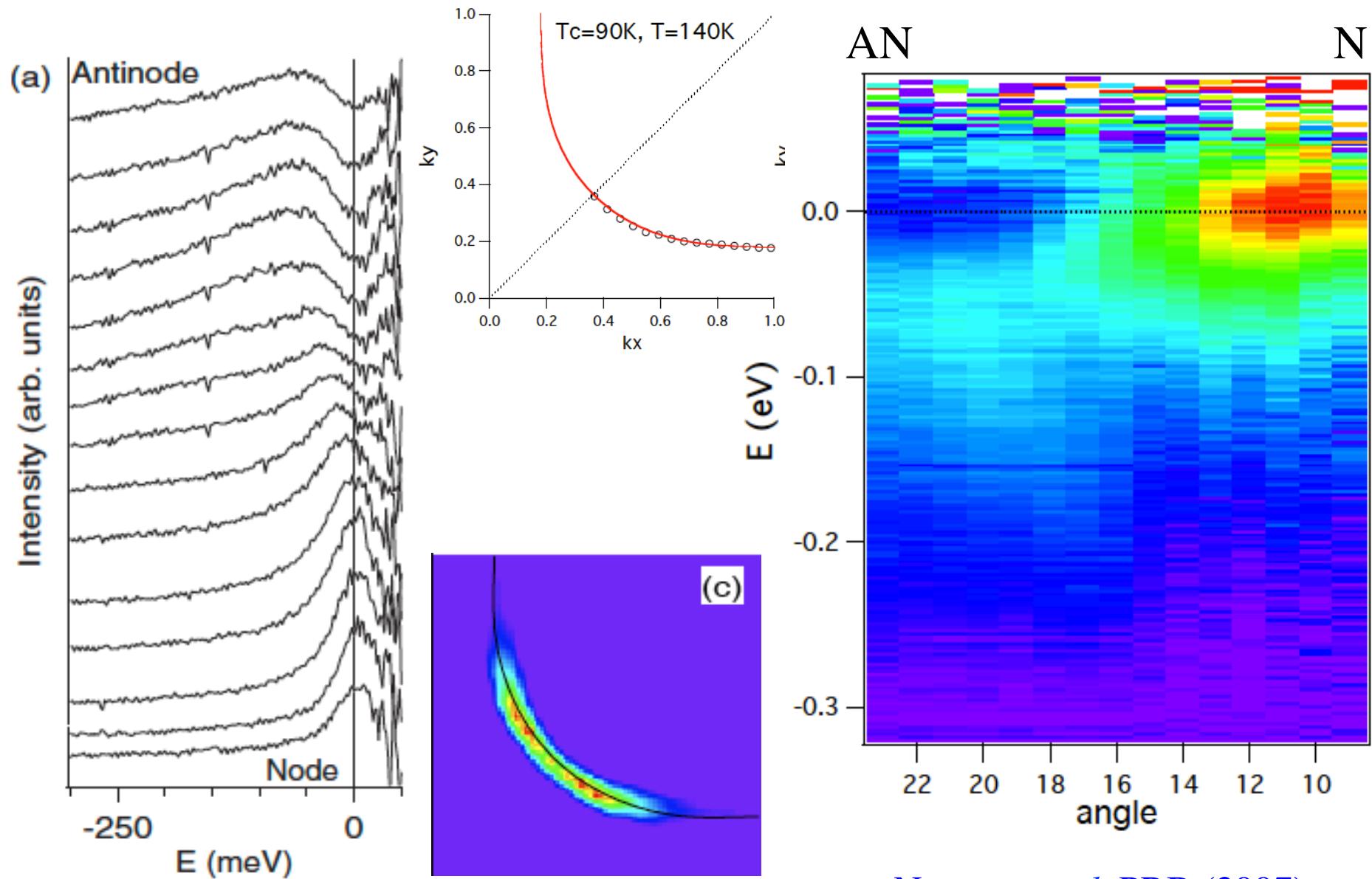
Natal – July 25, 2014



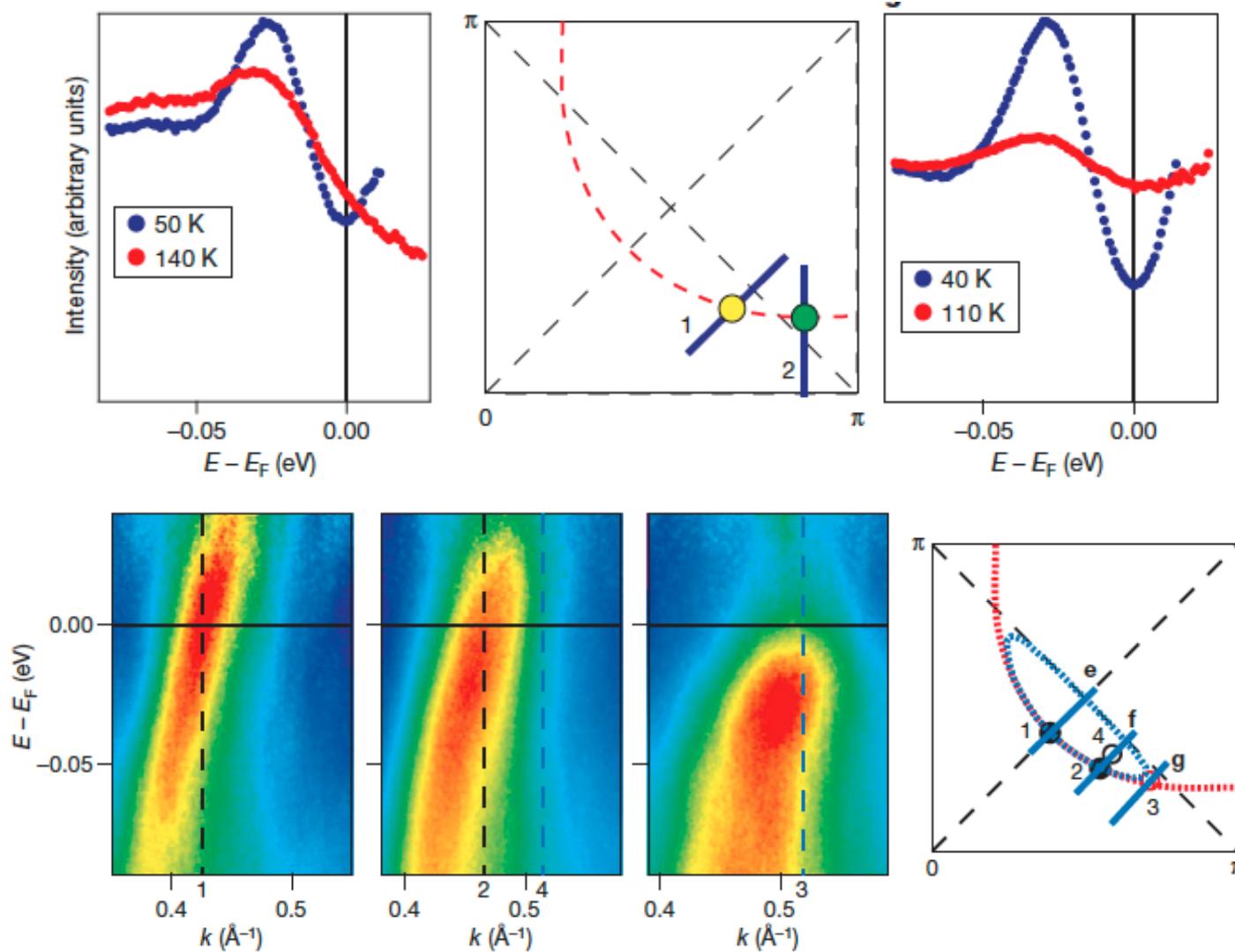
What is the Pseudogap Due to?

1. Spin singlets
2. Local pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

ARPES data from a Bi2212 single crystal ($T_c=90\text{K}$, $T=140\text{K}$)



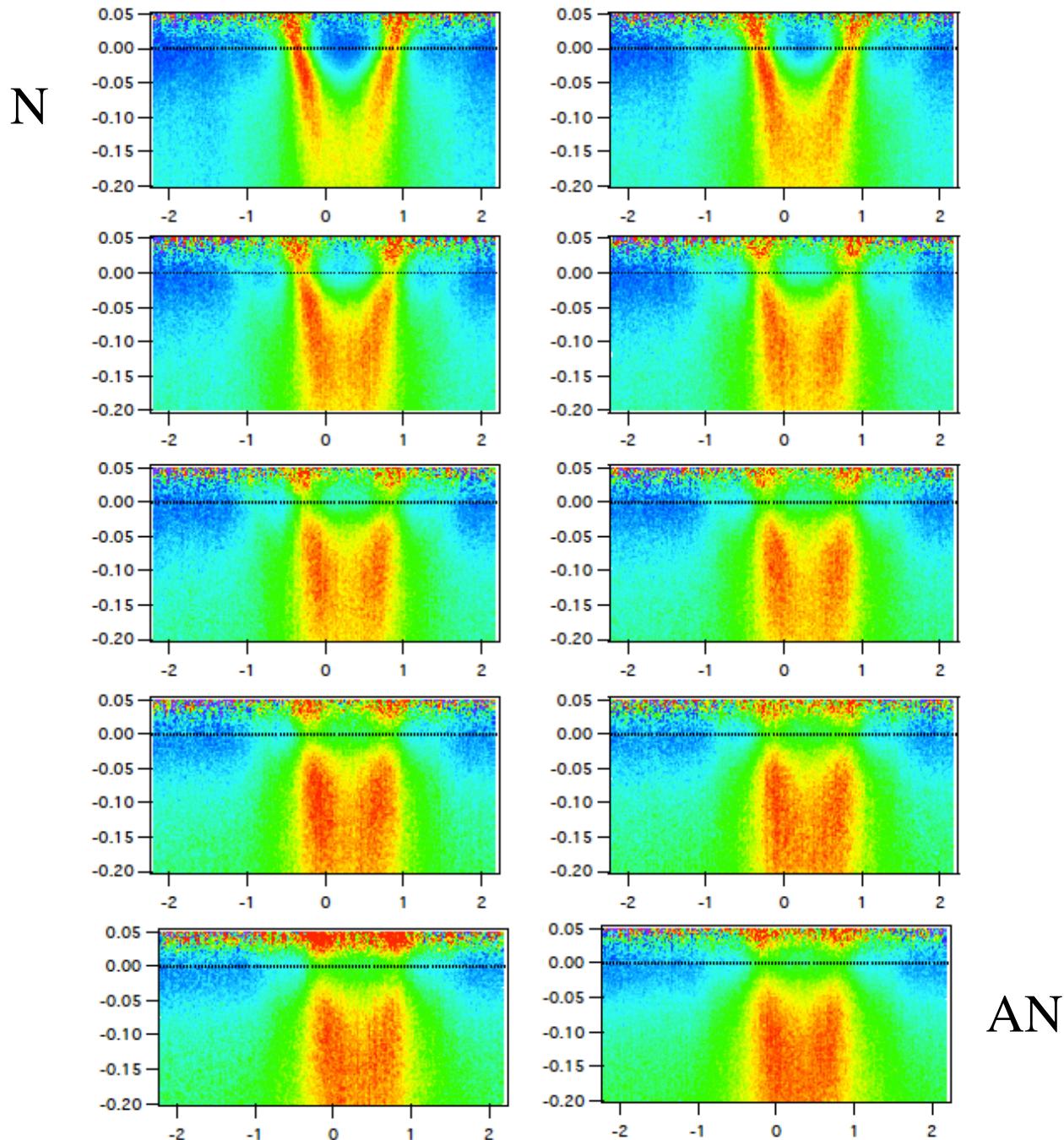
ARPES data from a Bi2212 single crystal ($T_c=65\text{K}$, $T=140\text{K}$)



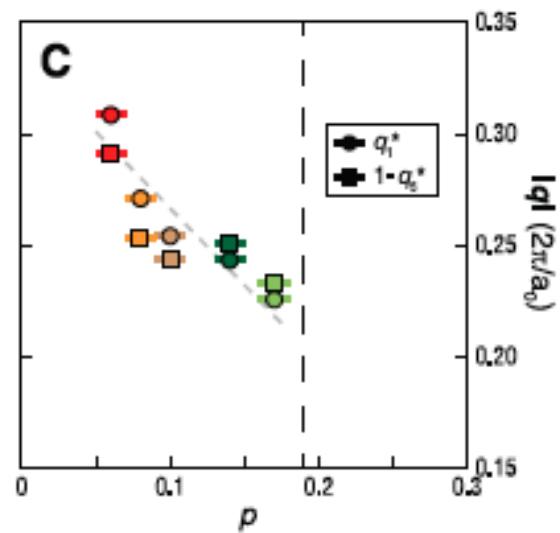
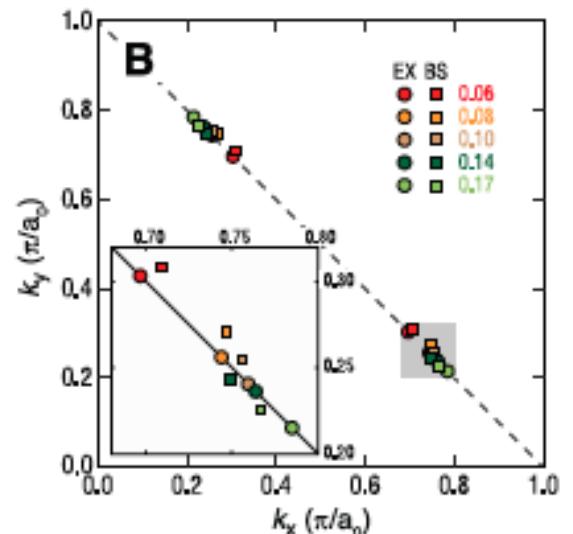
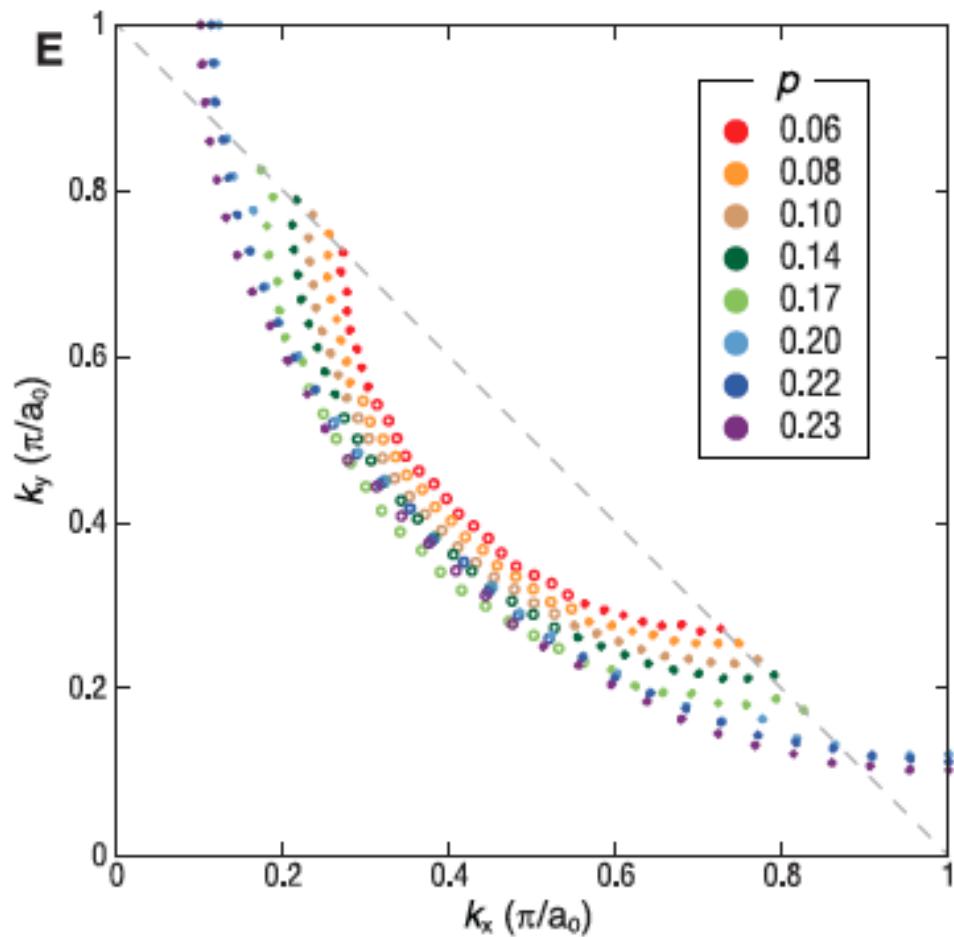
Yang *et al*, Nature (2008)

ARPES
Bi2212 film
 $T_c=67K$
 $T=120K$

p-h symmetry?

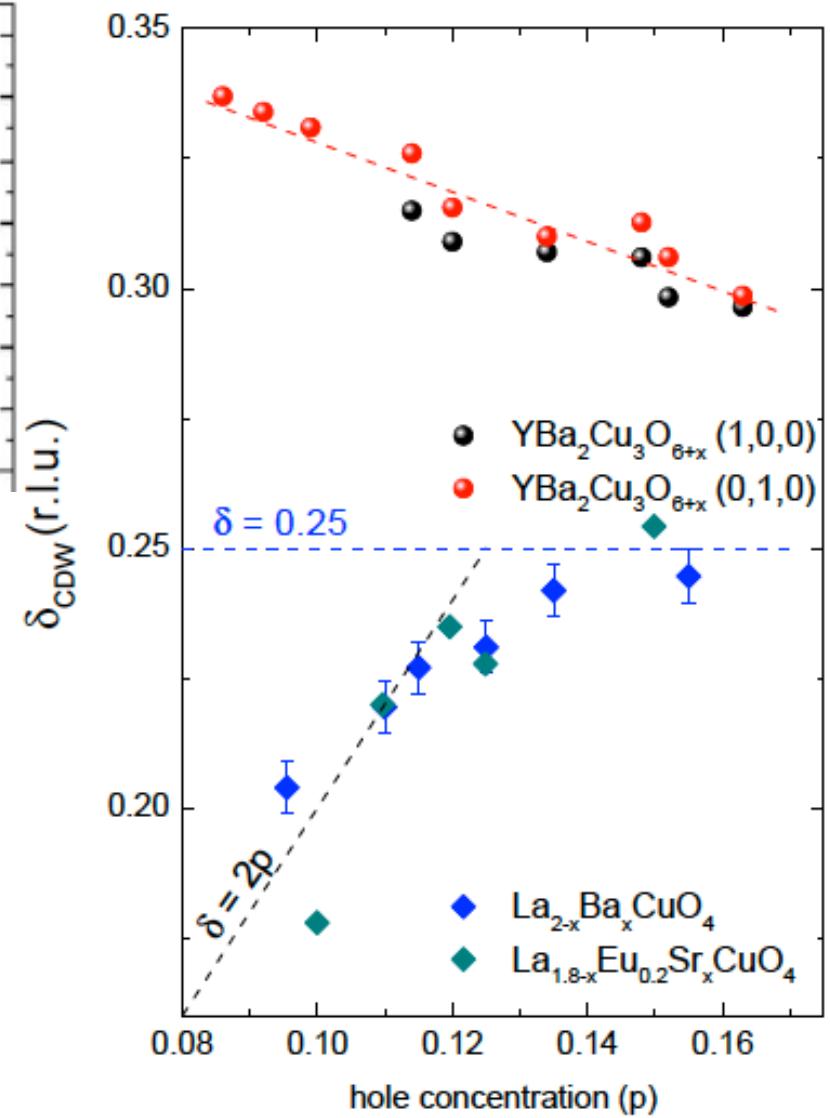
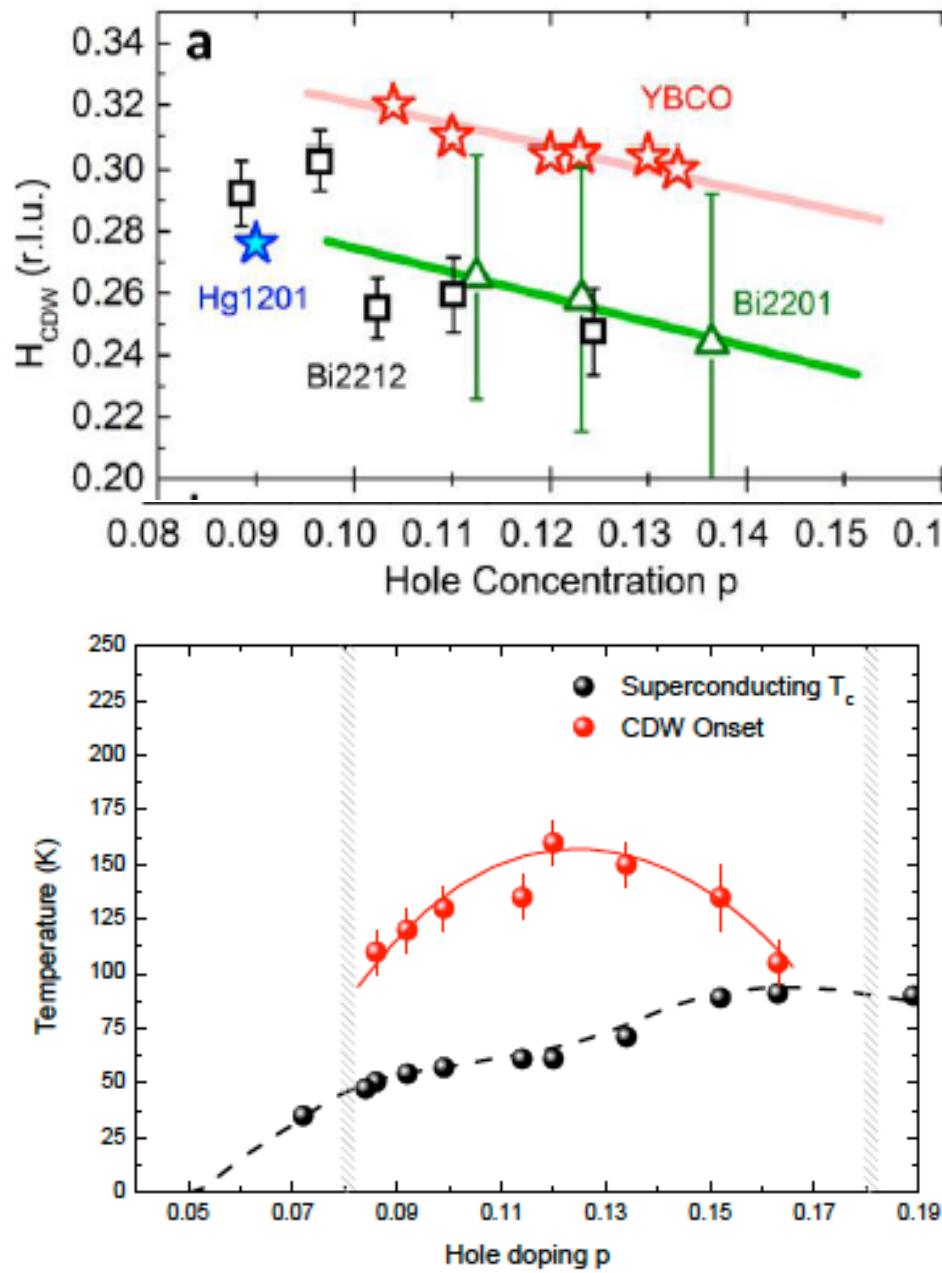


FT-STM data from Bi2212



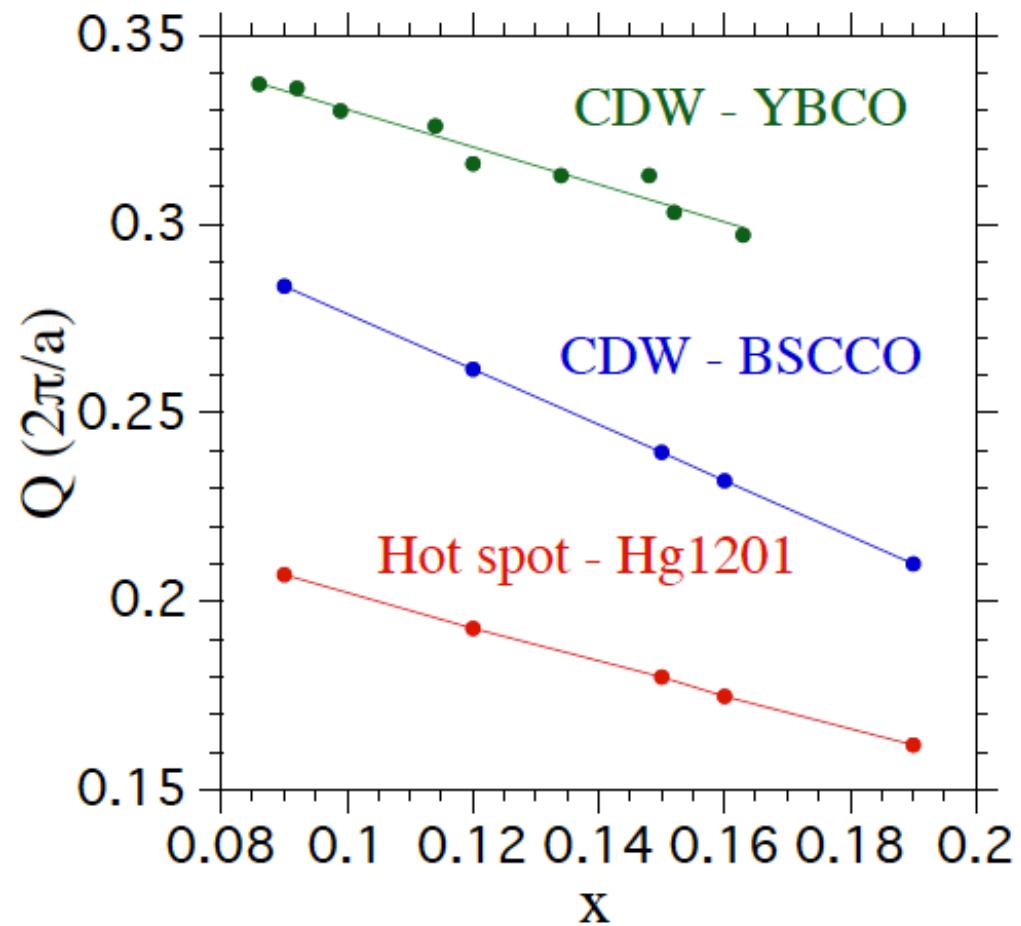
Fujita *et al*, Science (2014)

X-ray data from YBCO, Hg1201, Bi2201, Bi2212

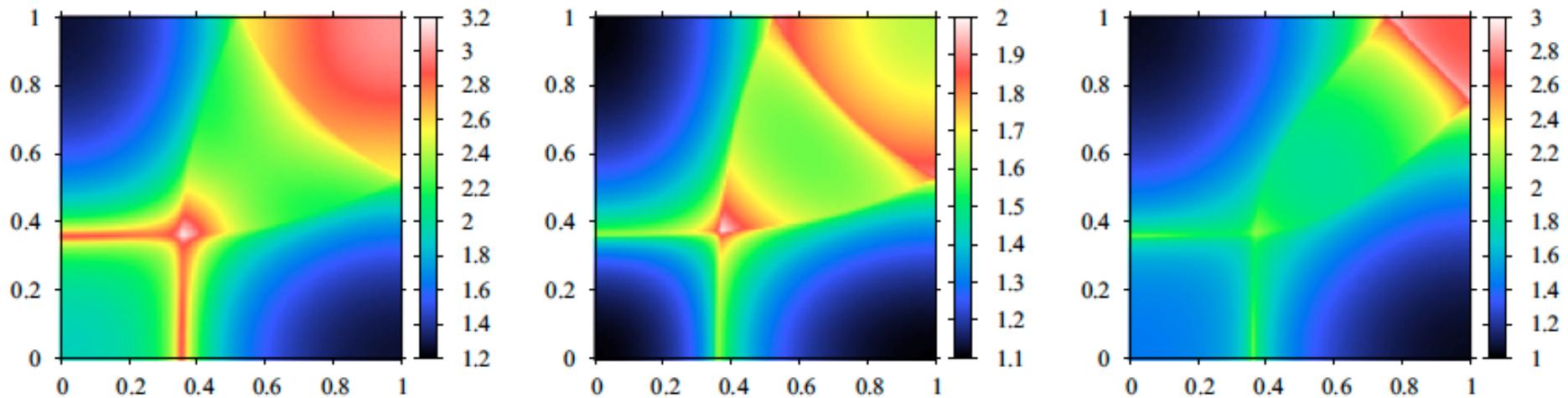


Tabis *et al*, arXiv (2014)
 Canosa *et al*, arXiv (2014)

Doping Dependence of the X-Ray Wave Vector



Bare Susceptibility

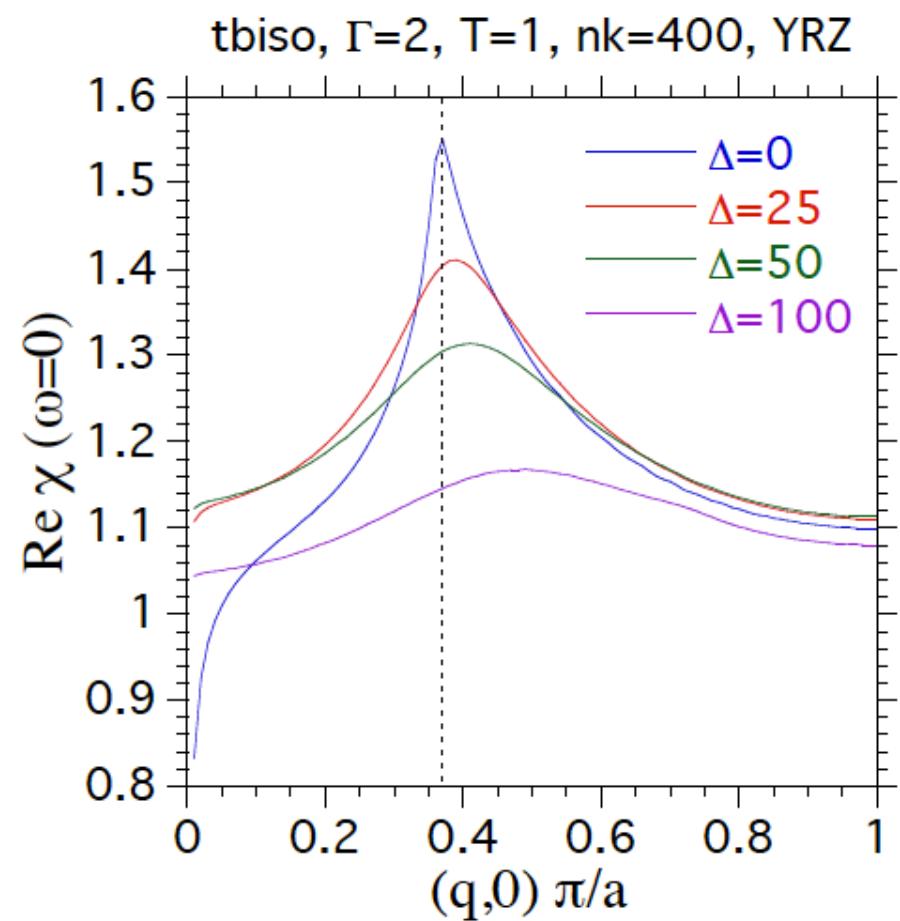
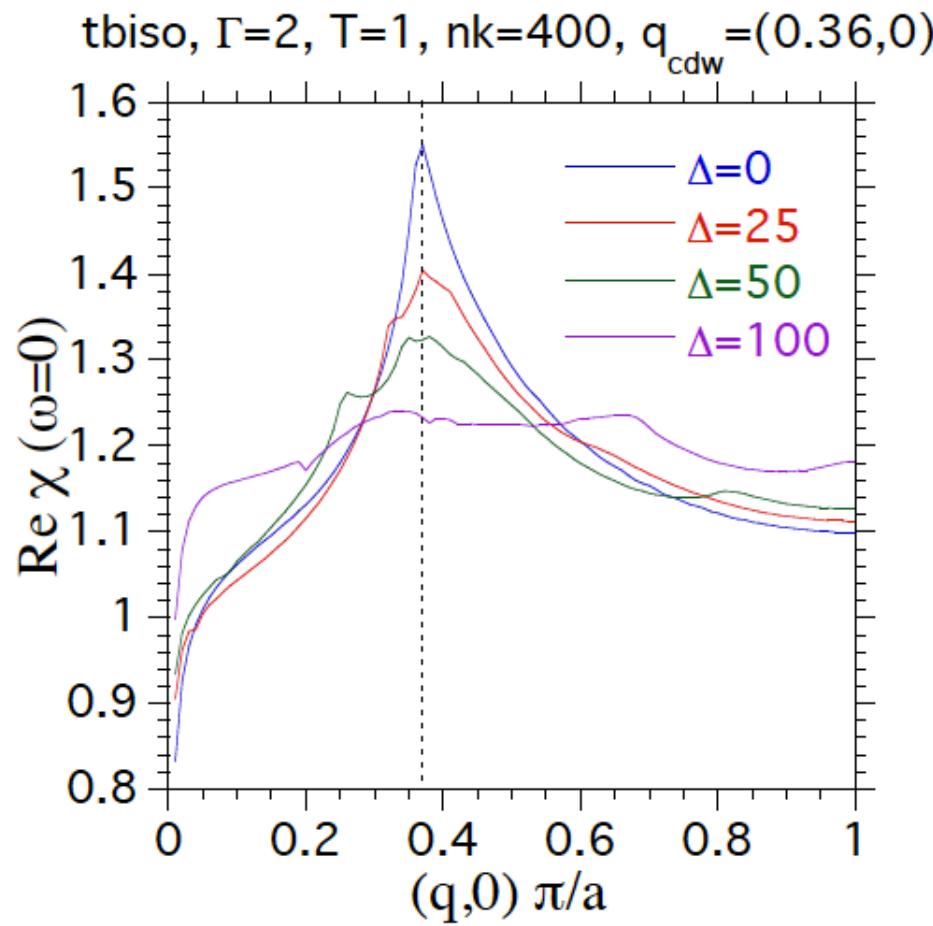


Bond maximum – antinodes

Diagonal maximum – hot spots

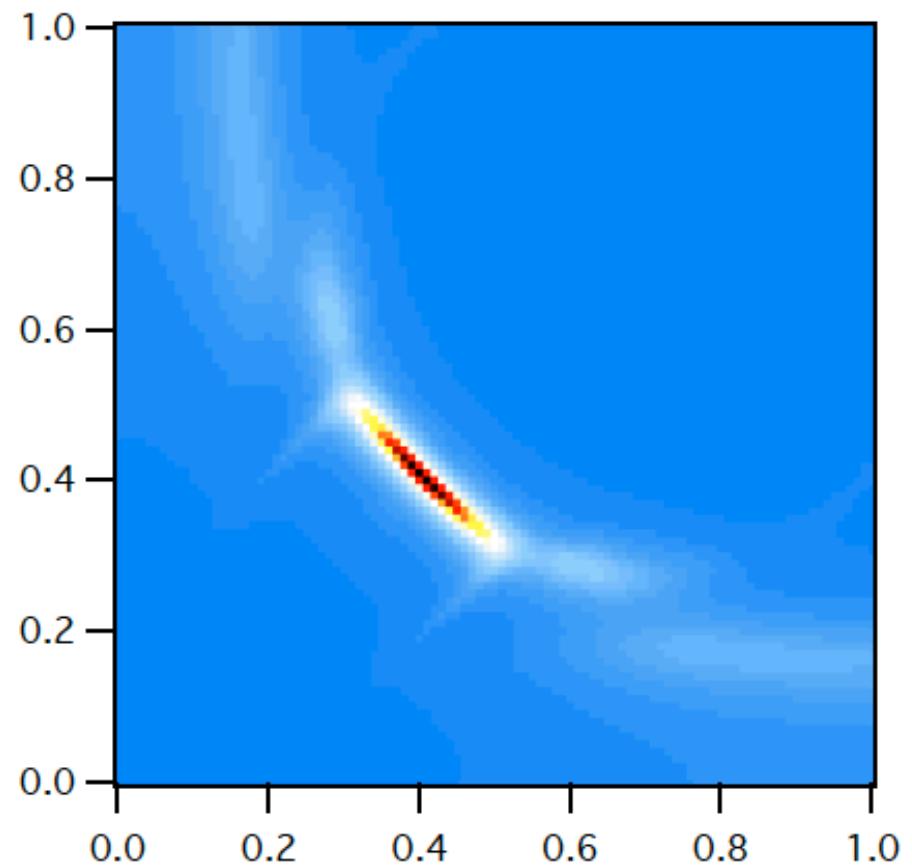
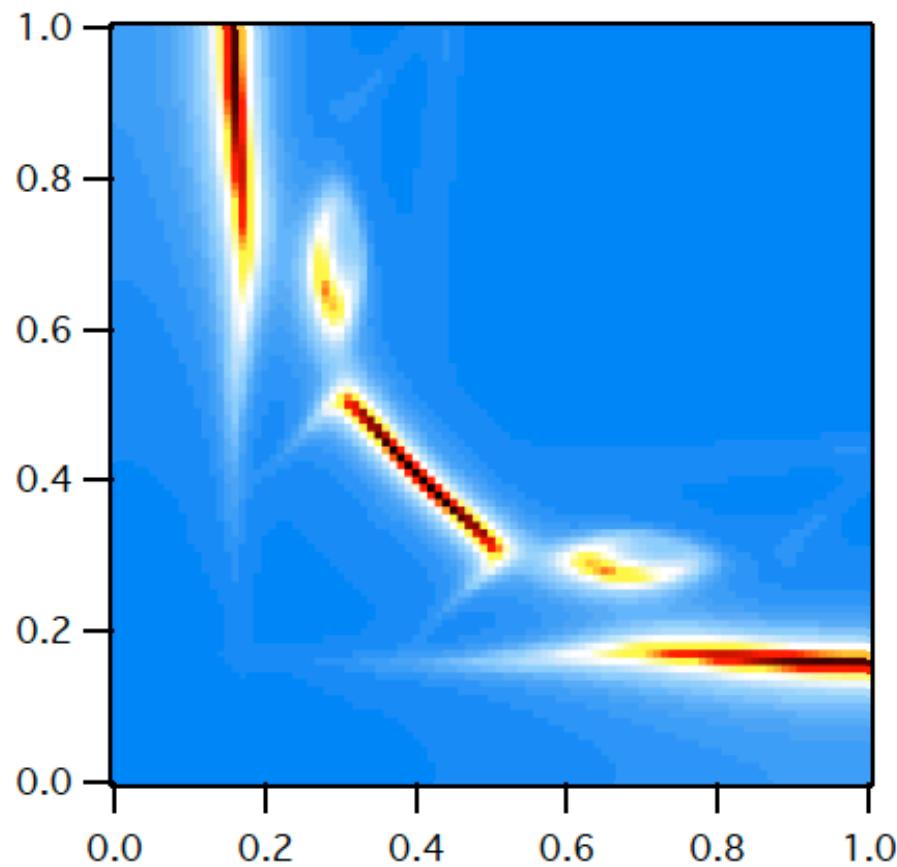
Norman, PRB (2007)
Melikyan & Norman, PRB (2014)

Bare Susceptibility vs CDW gap (left) and YRZ gap (right)



Biaxial Charge Order

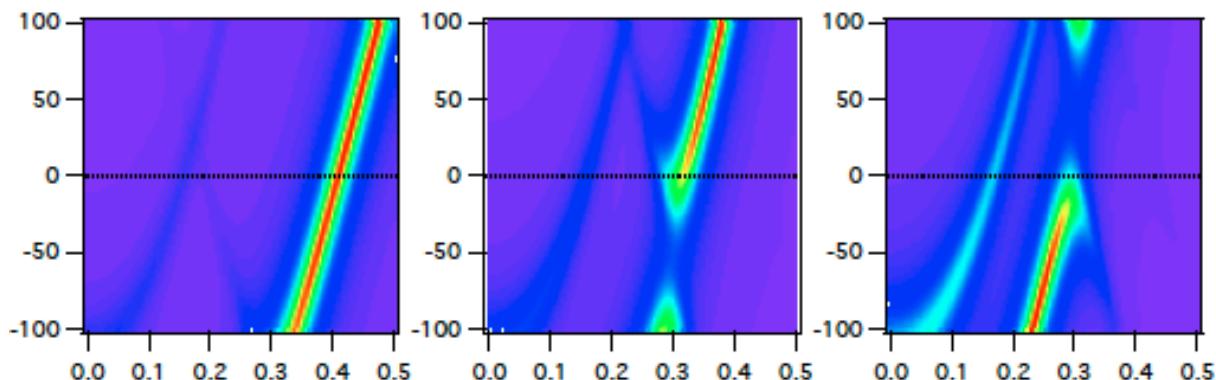
Allais et al, $t=300$ meV, $V=45$ meV, $\Gamma=20$ meV
 $\Delta=0$ meV (left), 45 meV (right)



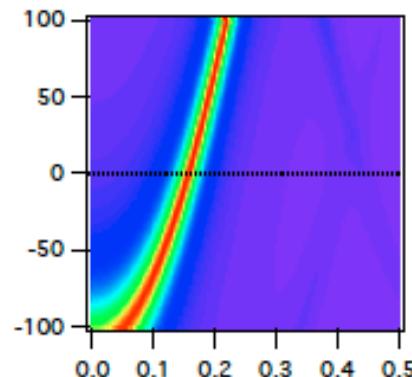
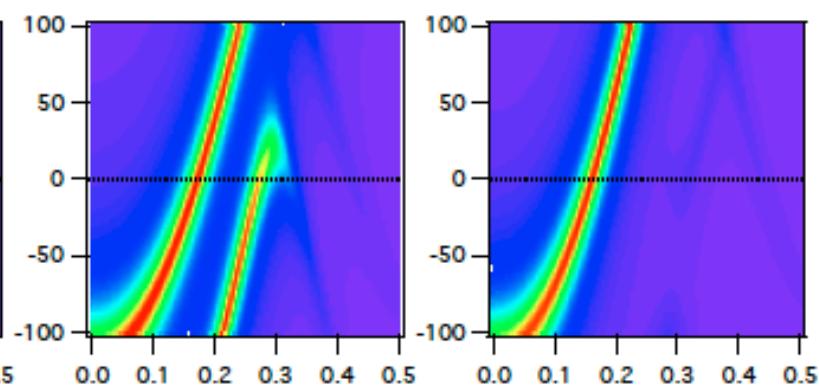
Allais *et al*, arXiv (2014)

CDW ($n=25$), Allais, $q=(.6,0)$, $t=300$, $\Delta=45$, $\Gamma=20$
 E (meV) vs k_y ; $k_x=0.5$ to 1.0 in steps of 0.1

Node

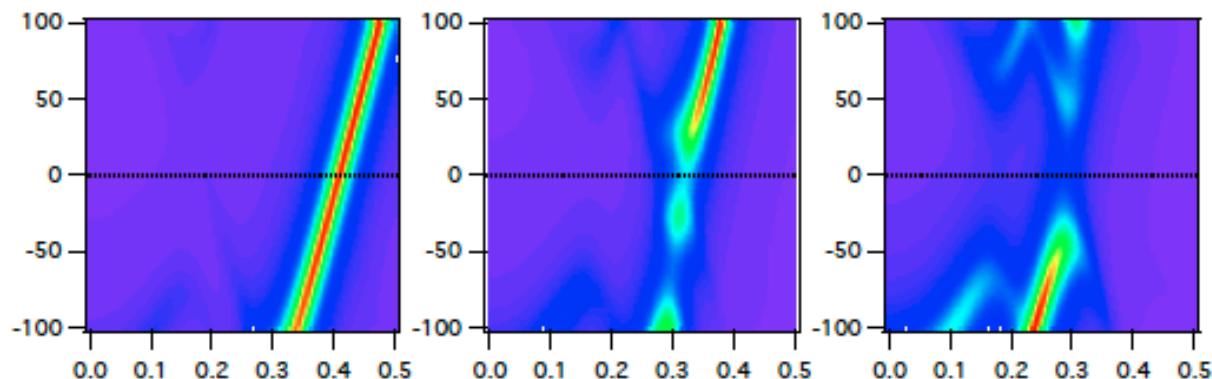


Antinode

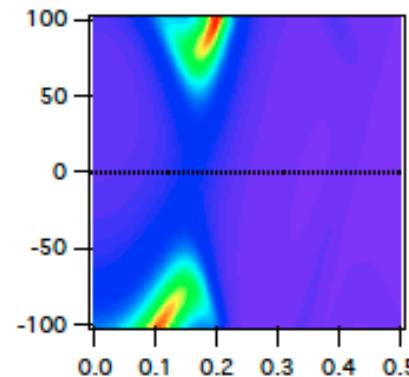
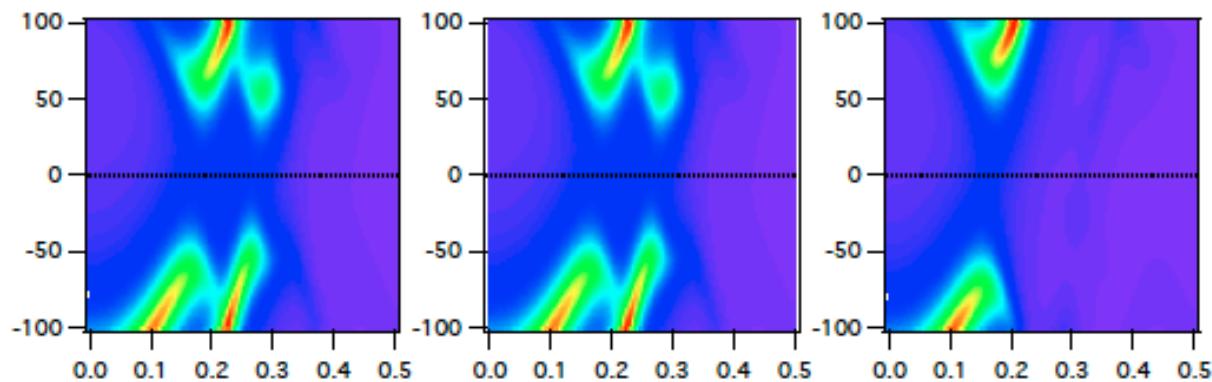


CDW ($n=25$), Allais, $q=(.6,0)$, $t=300$, $\Delta=45$, $\Gamma=20$
SC+bond, E (meV) vs k_y ; $k_x=0.5$ to 1.0 in steps of 0.1

Node

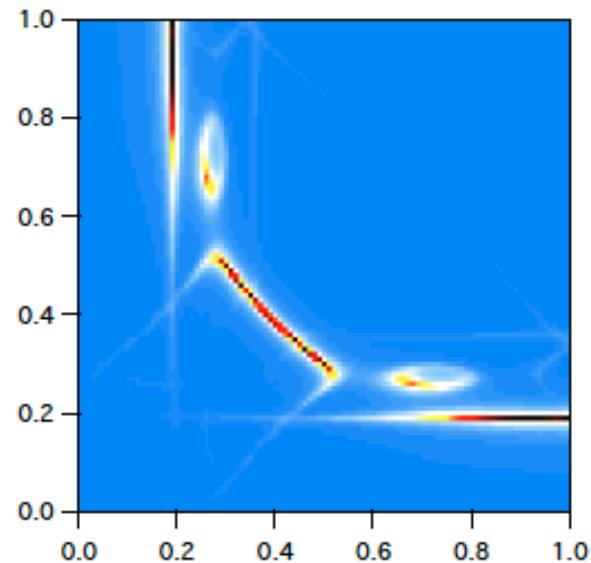
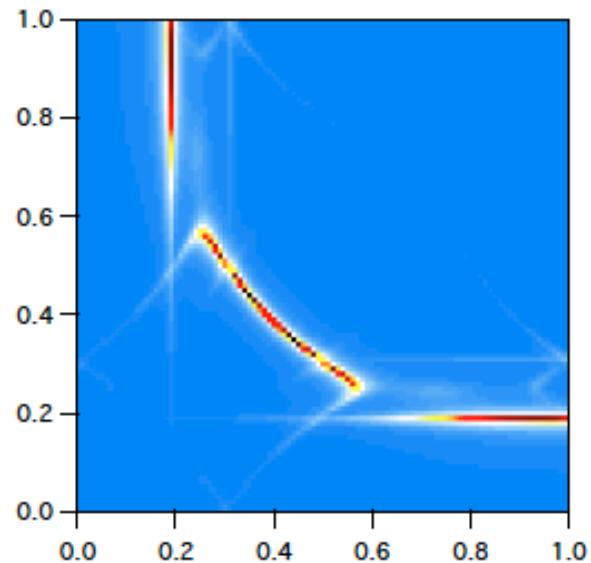
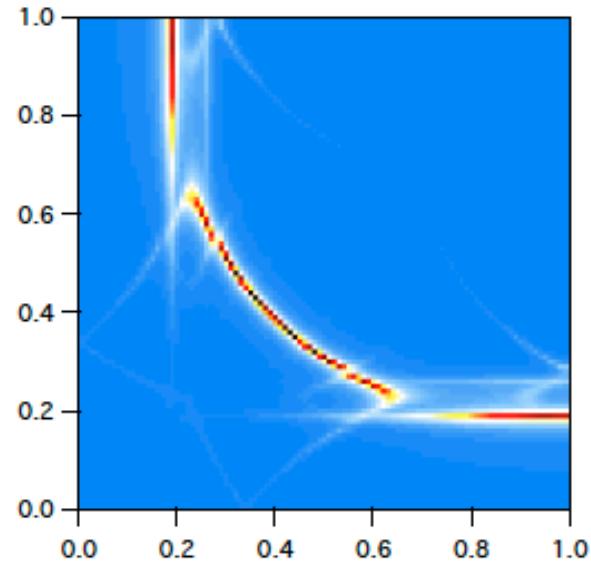
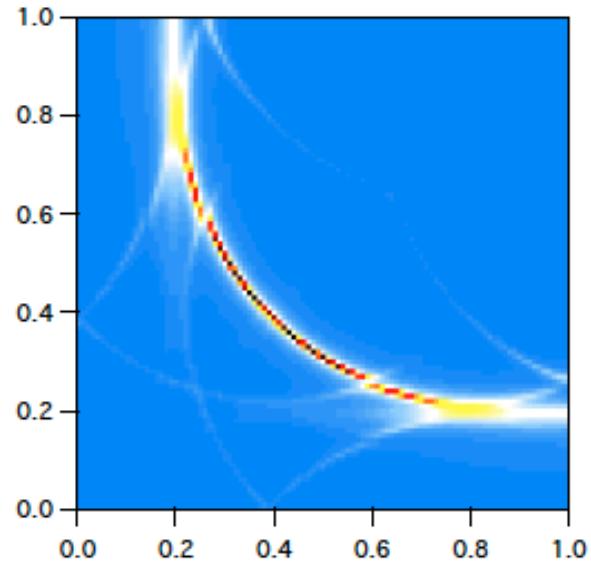


Antinode

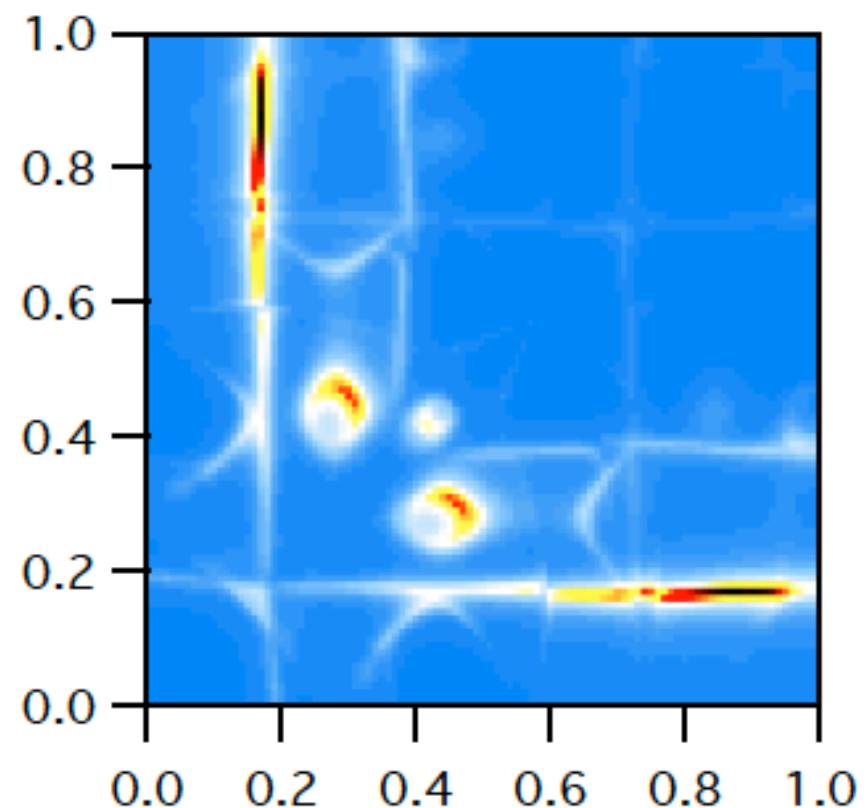
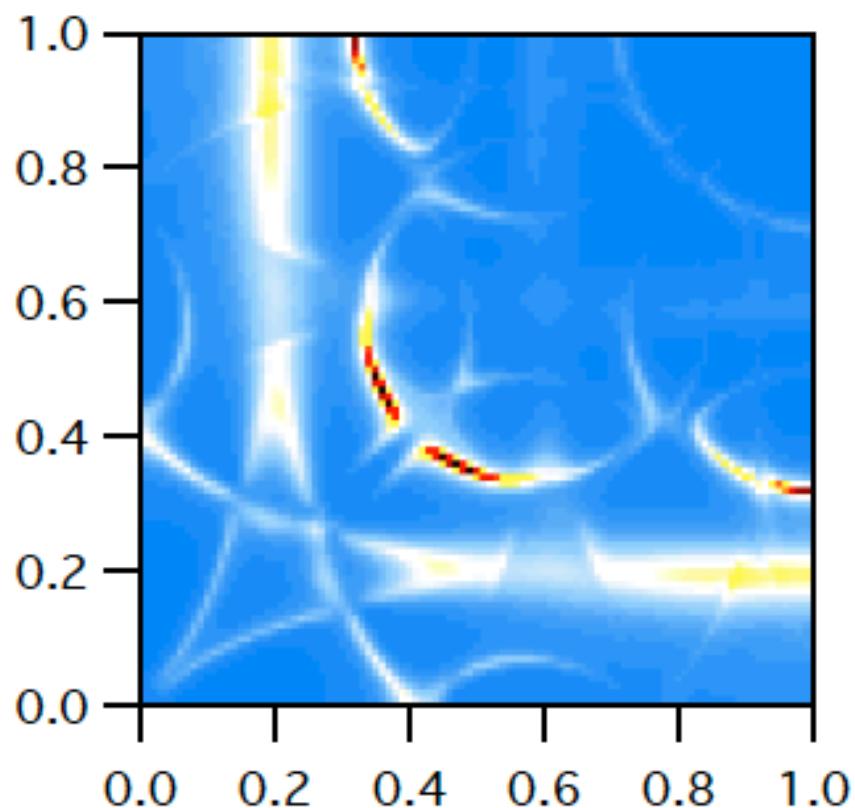


Hg1201 ($x=0.1$), $V=0.1$ eV

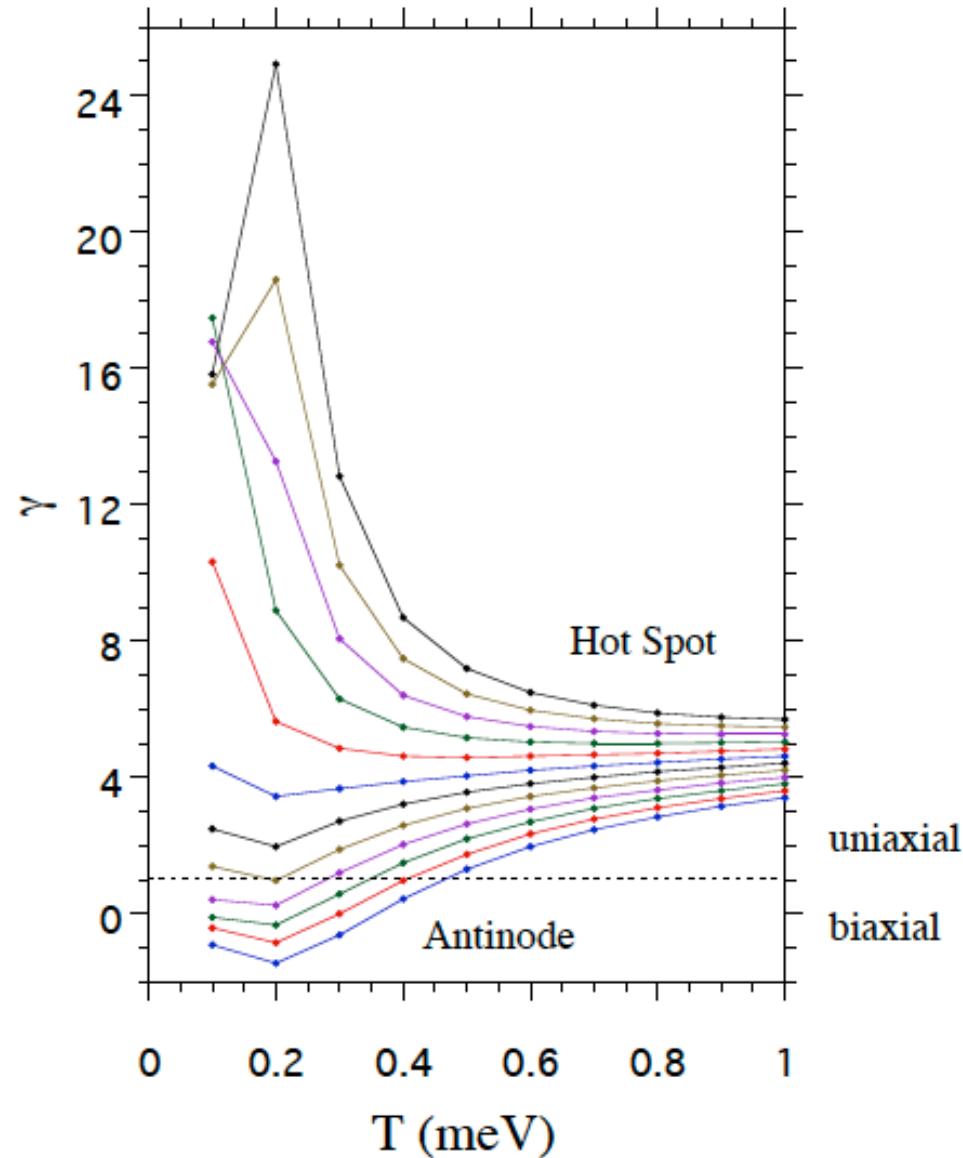
(top L: $Q=0.2$, top R: $Q=0.225$, bottom L: $Q=0.25$, bottom R: $Q=0.275$)



Hg1201 ($x=0.1$), $V=0.3$ eV
(left: $Q=0.2$, right: $Q=0.275$)



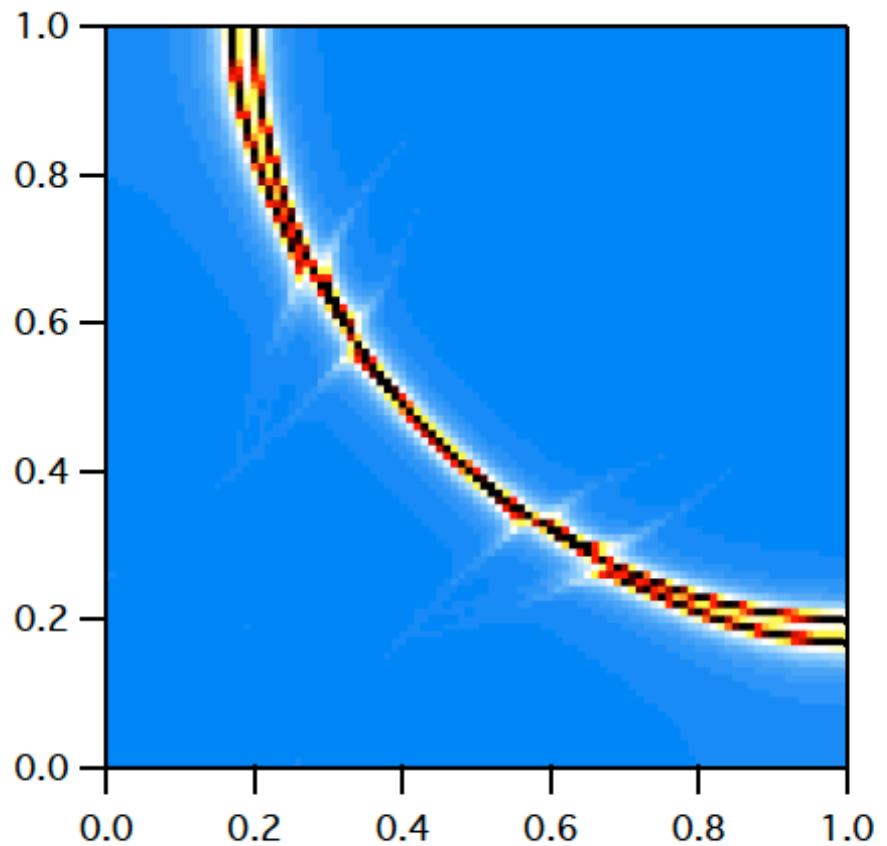
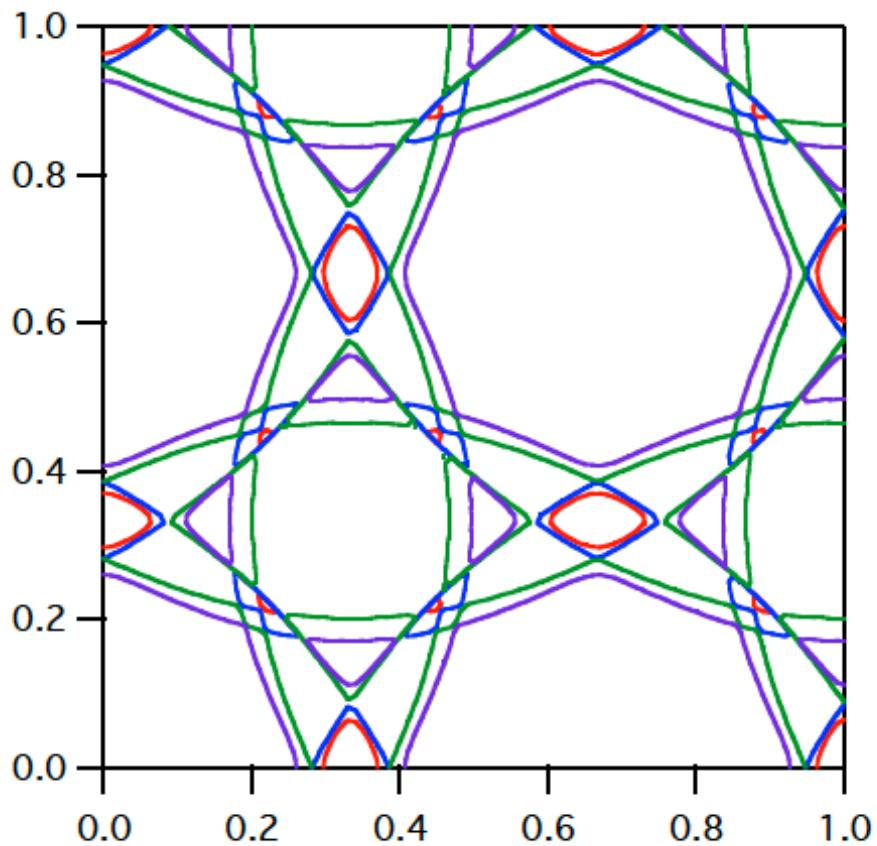
Stripe versus checkerboard order



$$\gamma \sim x^2y^2/(x^4+y^4)$$

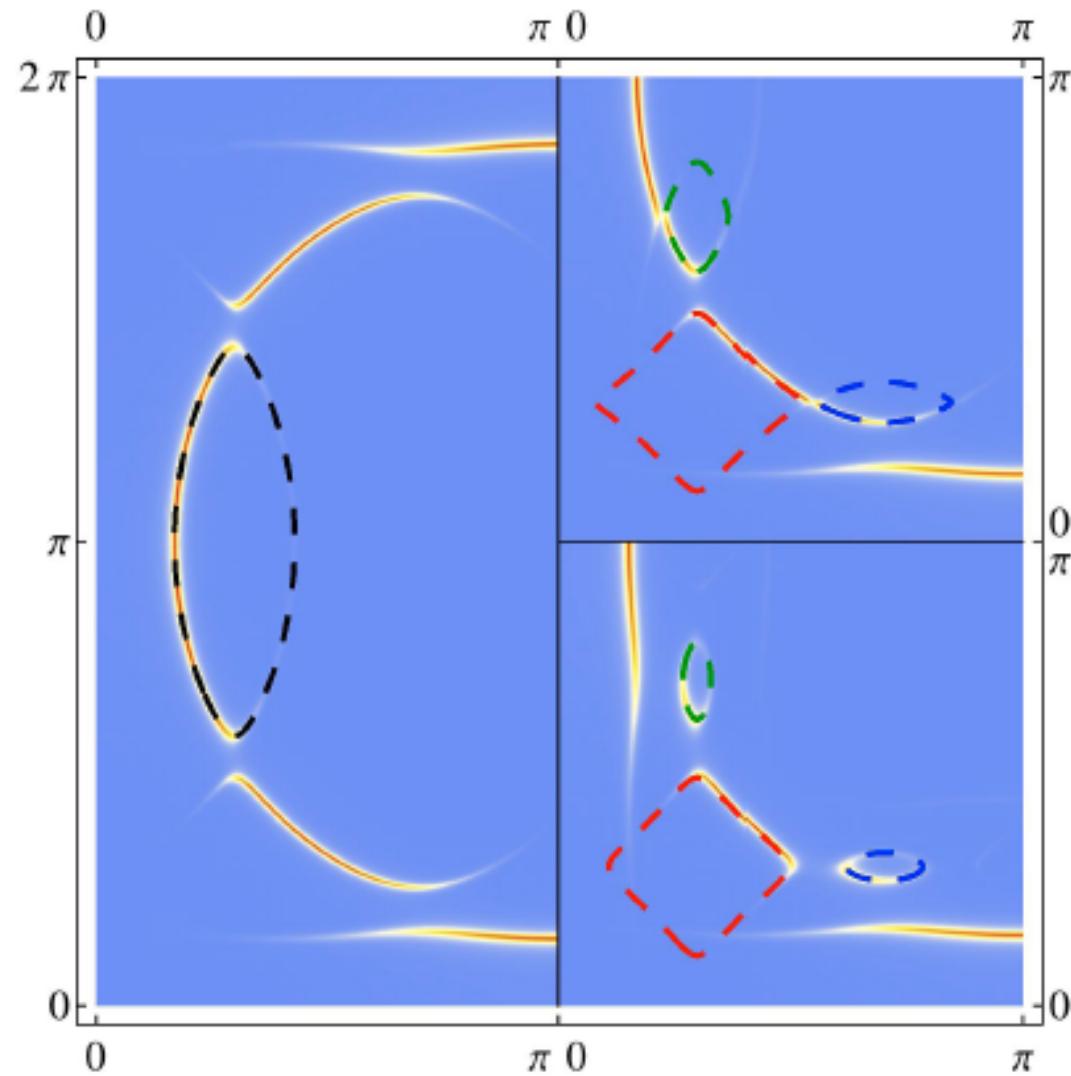
Melikyan & Norman, PRB (2014)

Criss crossed stripes ($x=0$, $Q=1/3$, $t=300$, $V_x=30$, $V_y=3$)



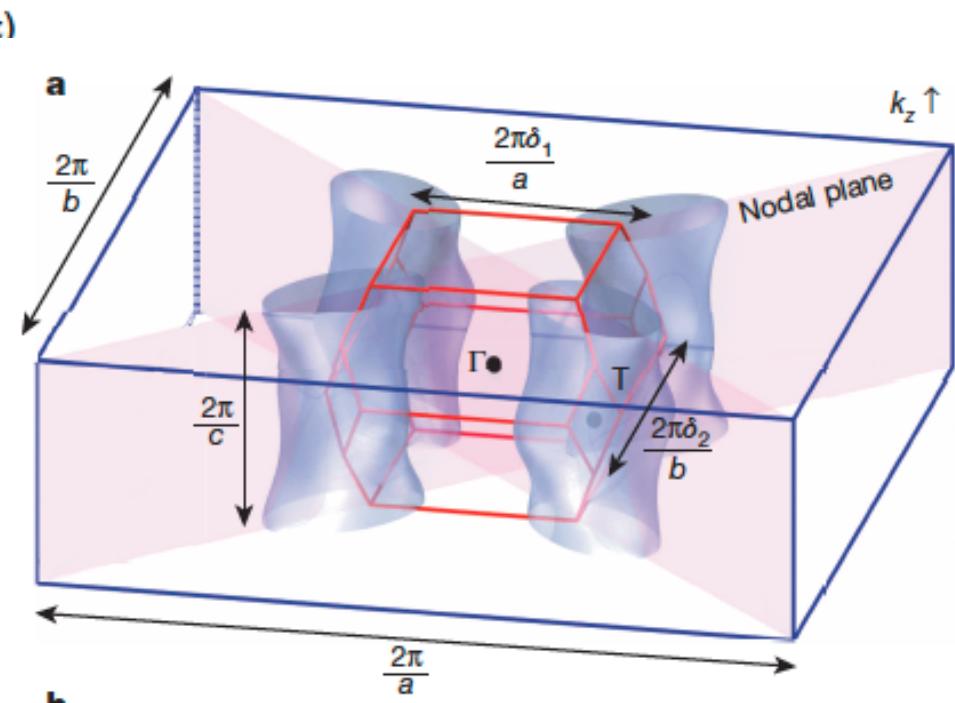
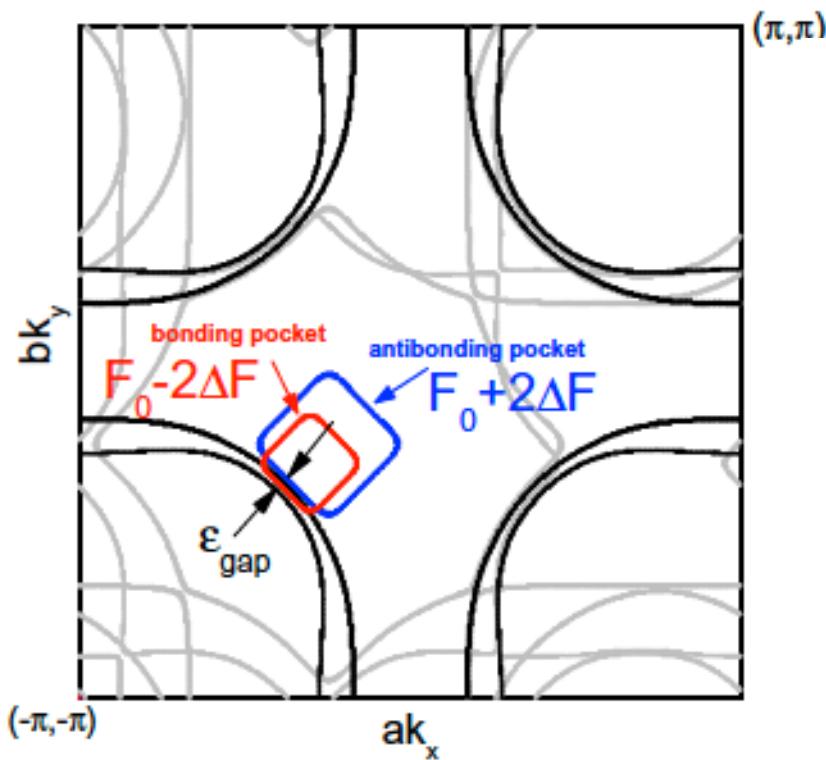
Maharaj *et al*, arXiv (2014)

Uniaxial Order ($V_y \ll V_x$)



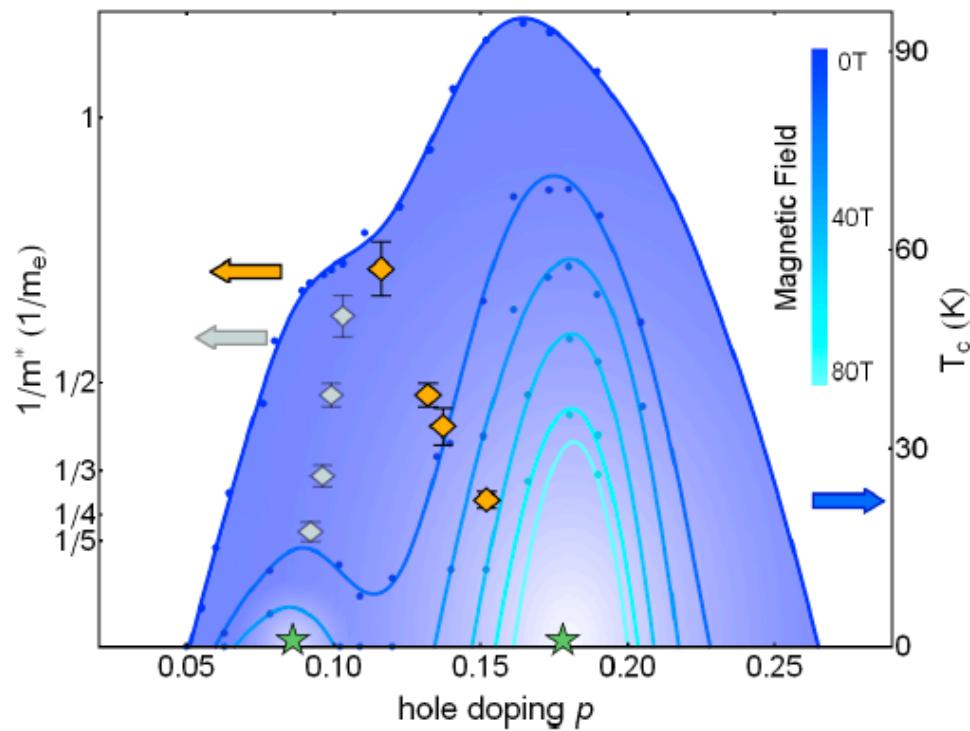
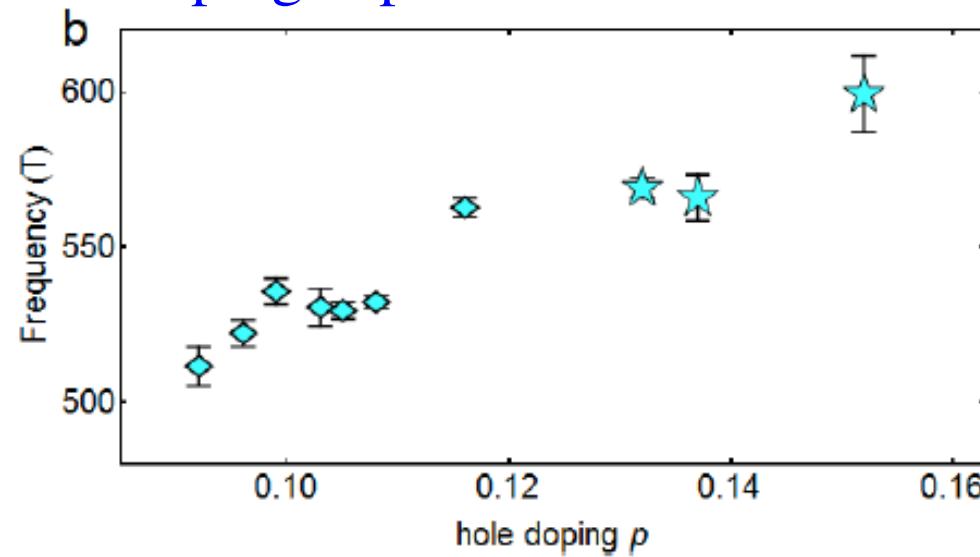
Allais *et al*, arXiv (2014)

Nodal pocket model of Harrison & Sebastian

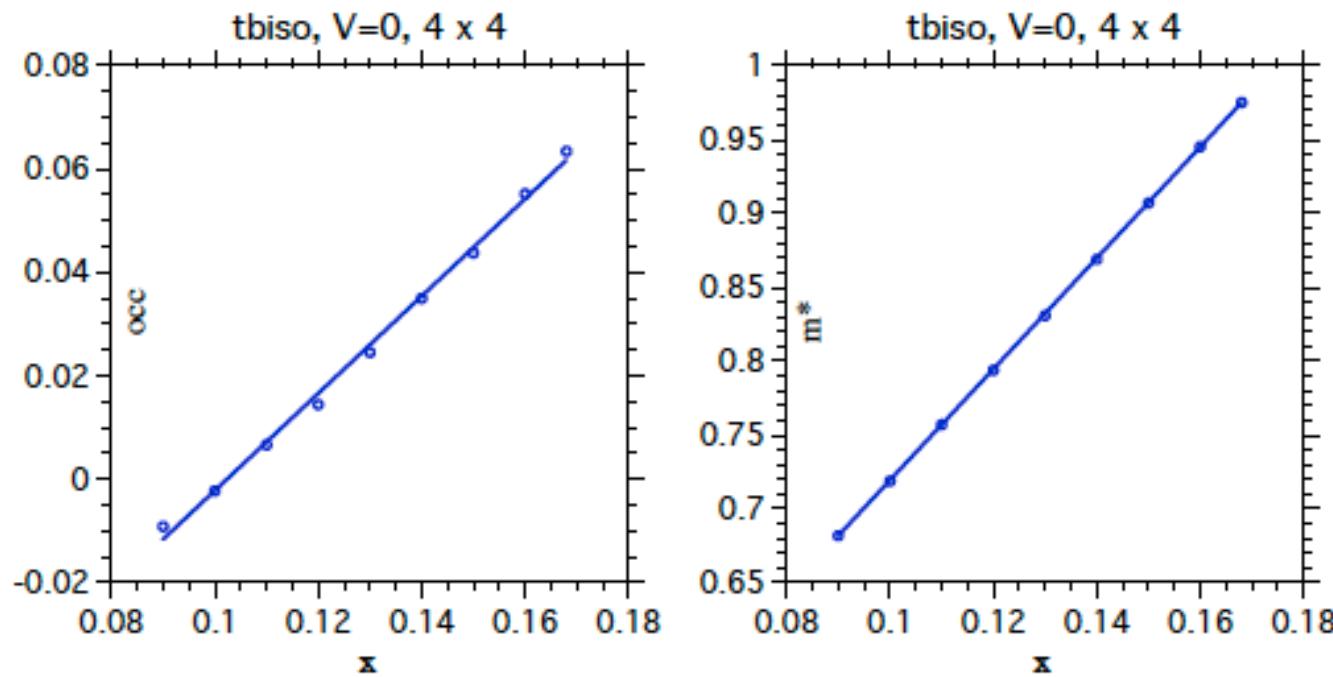
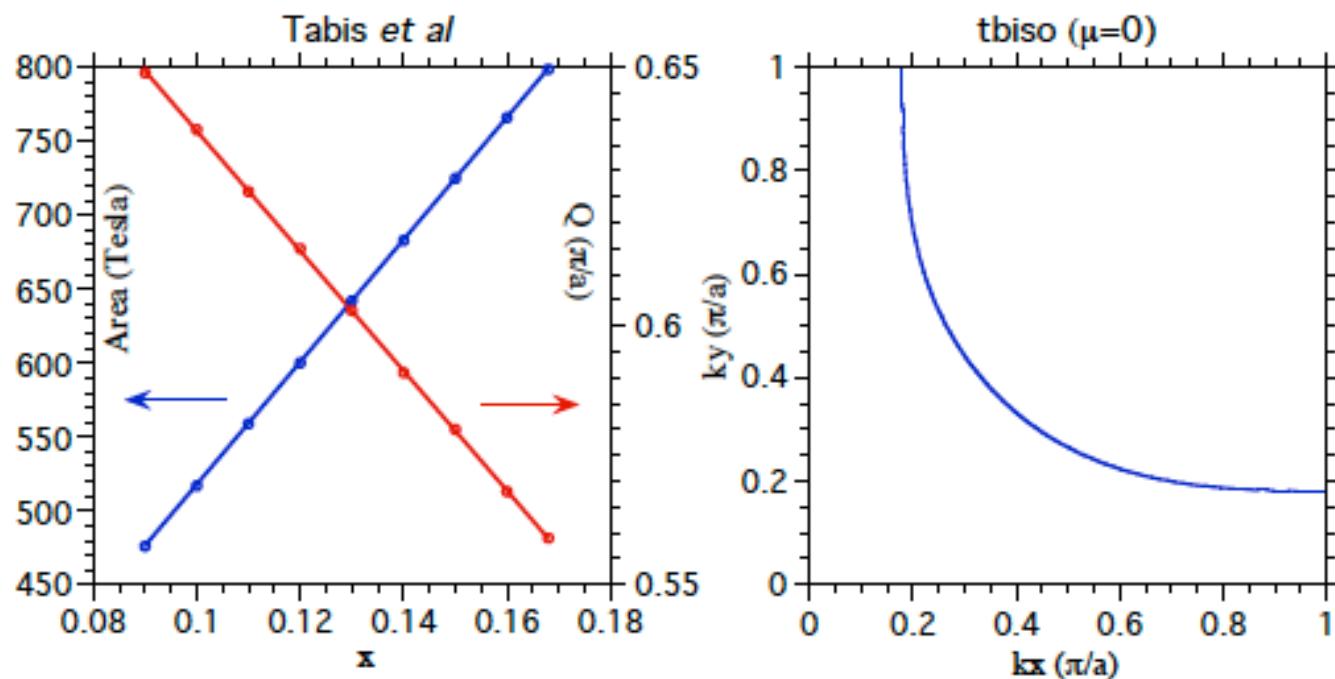


Harrison & Sebastian, NJP (2012)
Sebastian *et al*, Nature (2014)

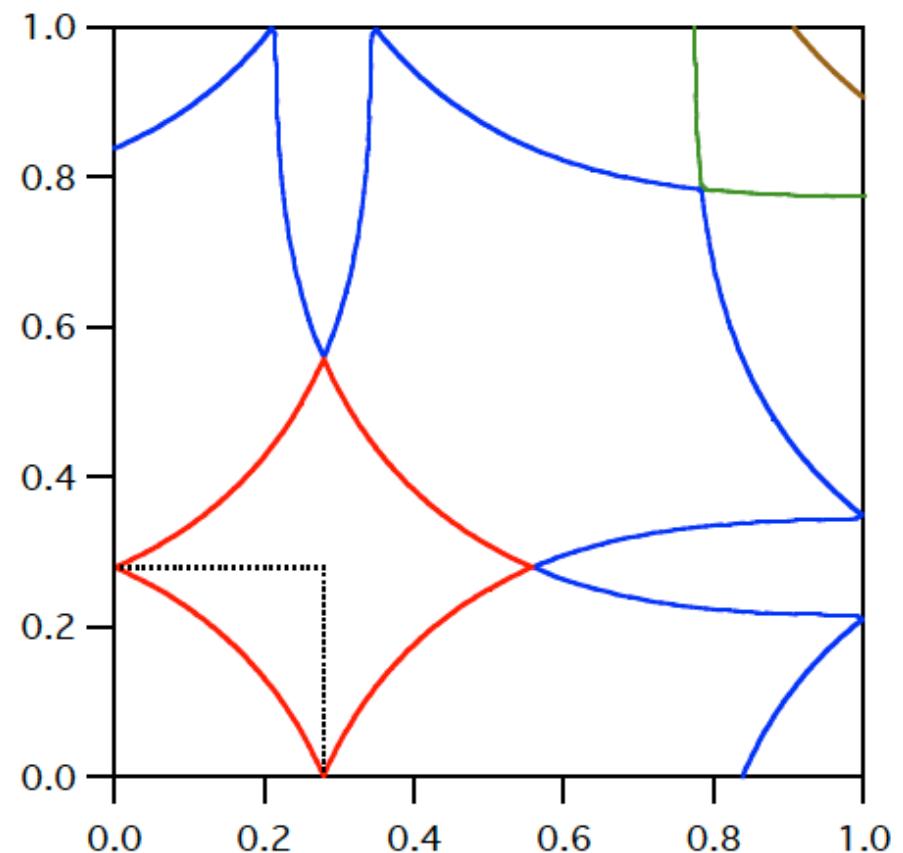
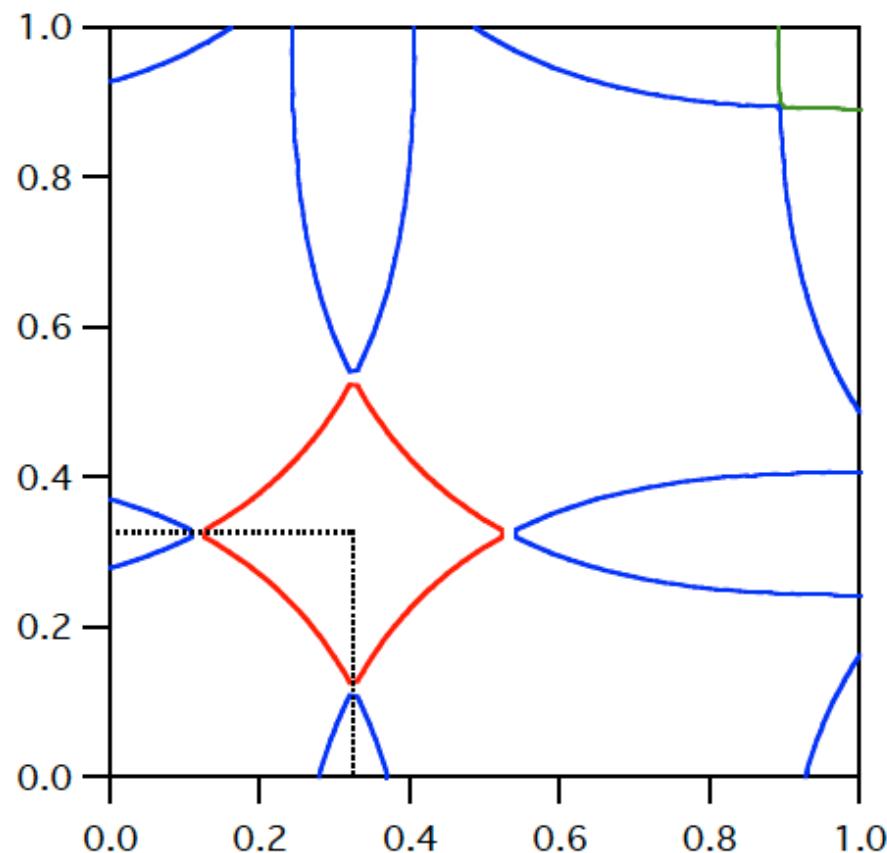
Doping dependence of dHvA data



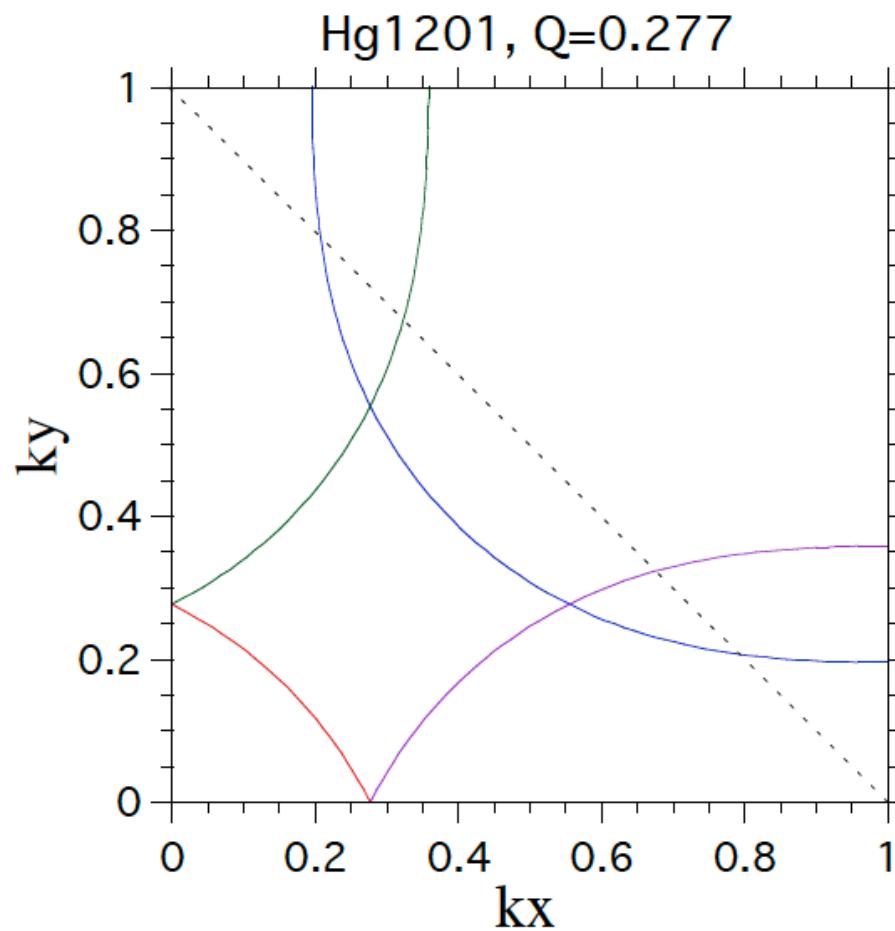
Ramshaw *et al*, unpublished



Tabis-Neil, tbiso, 4 x 4, V=0
 $x=0.09$ (left) and 0.168 (right)

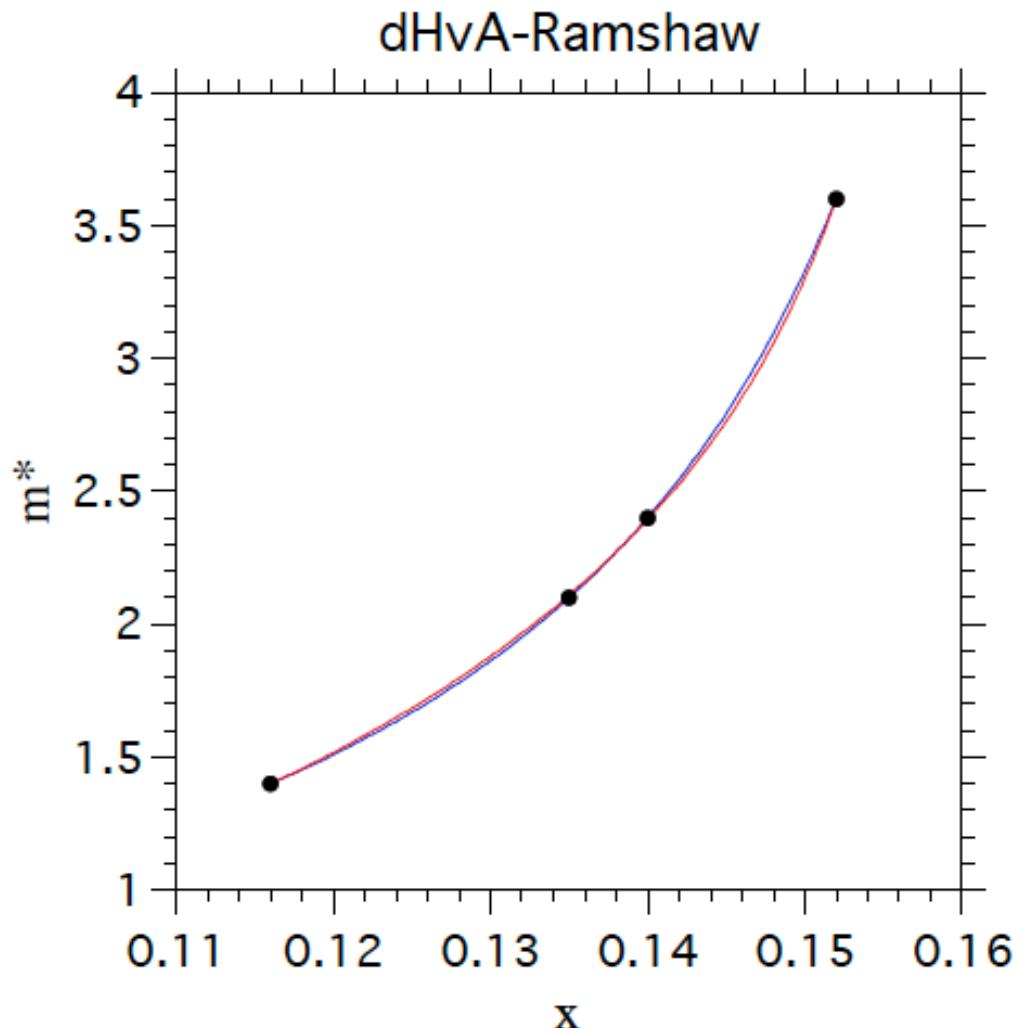


Nodal pocket for Hg1201 ($x=0.09$) near Lifshitz point



Tabis *et al*, arXiv (2014)

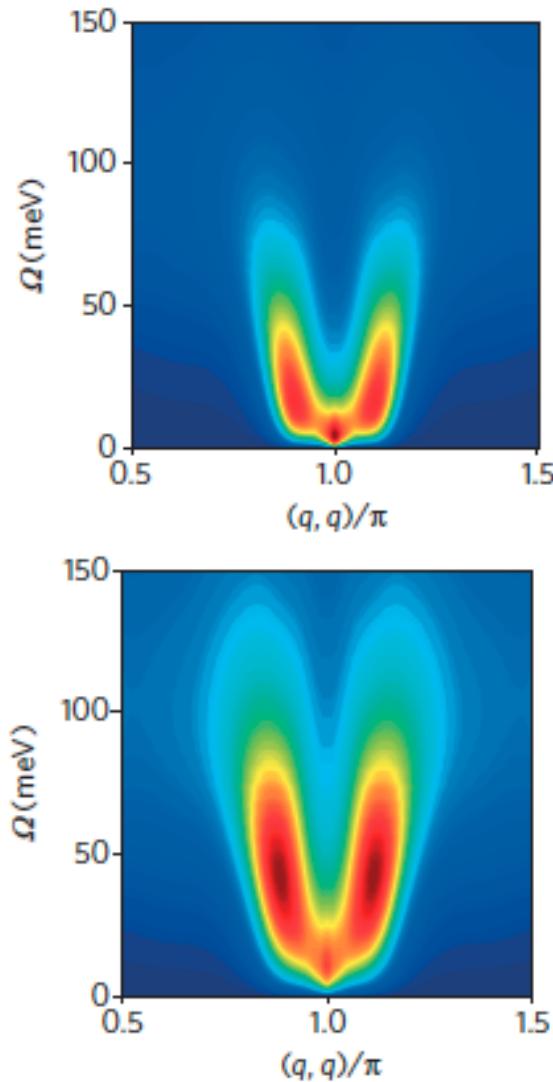
Lifshitz transition?



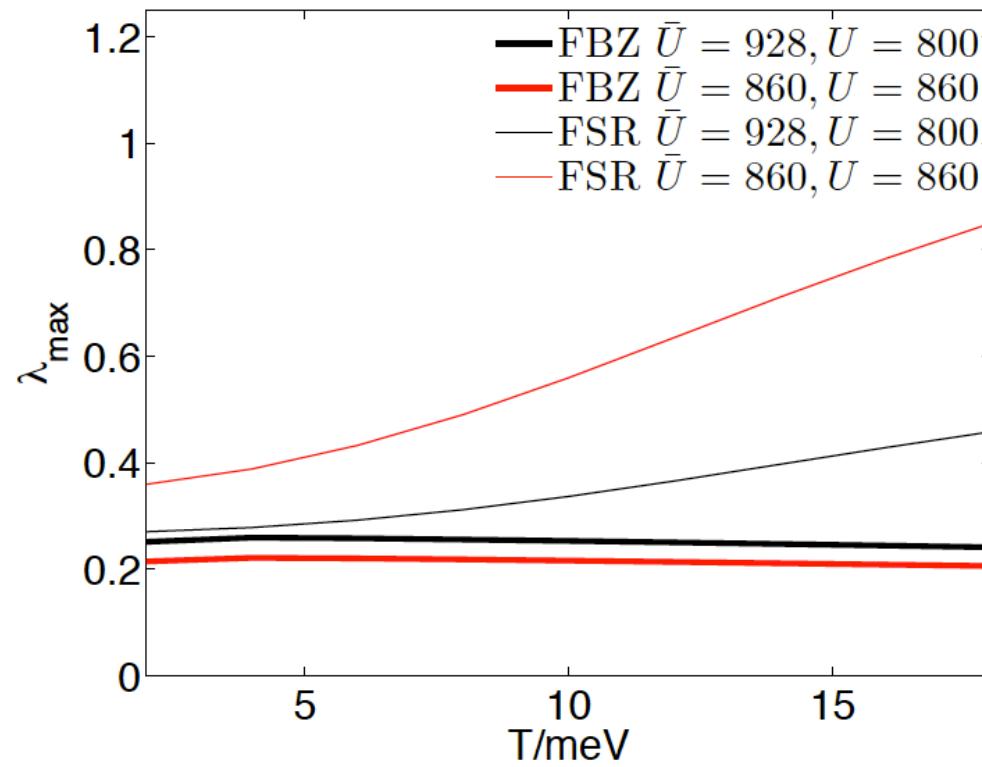
y = m1 + m2/(m3-m0)		
	Value	Error
m1	-0.17339	0.0046834
m2	0.097164	0.00035682
m3	0.17775	6.5203e-5
Chisq	5.5479e-7	NA
R	1	NA

y = m1 + m2*log(m3-m0)		
	Value	Error
m1	-2.449	0.11242
m2	-2.8179	0.084831
m3	0.15913	0.00043697
Chisq	0.00013117	NA
R	0.99997	NA

d-wave eigenvalue versus temperature using ARPES Greens functions
(FBZ is full Brillouin zone, FSR is Fermi surface restricted)

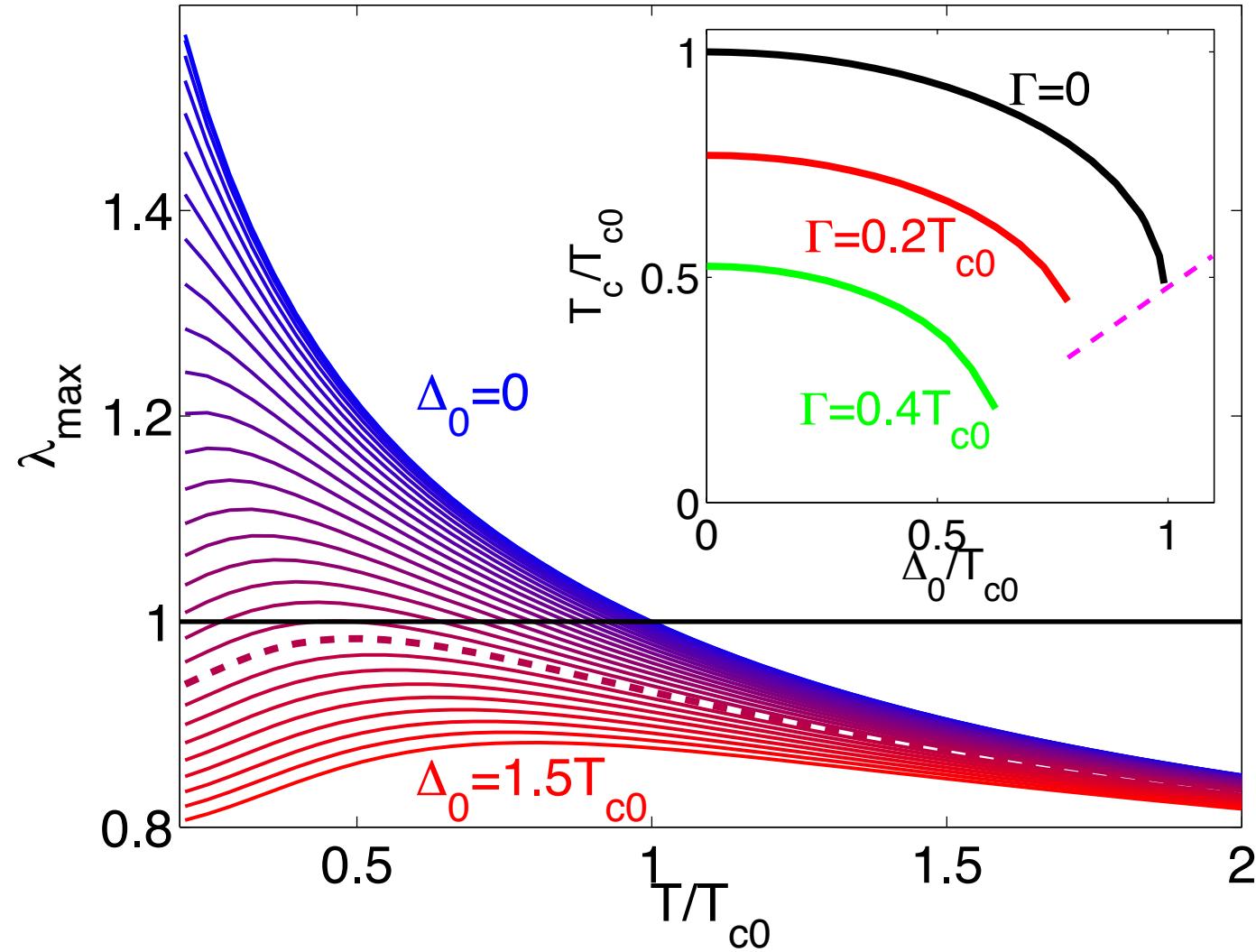


$\text{Im } \chi(q, \Omega)$

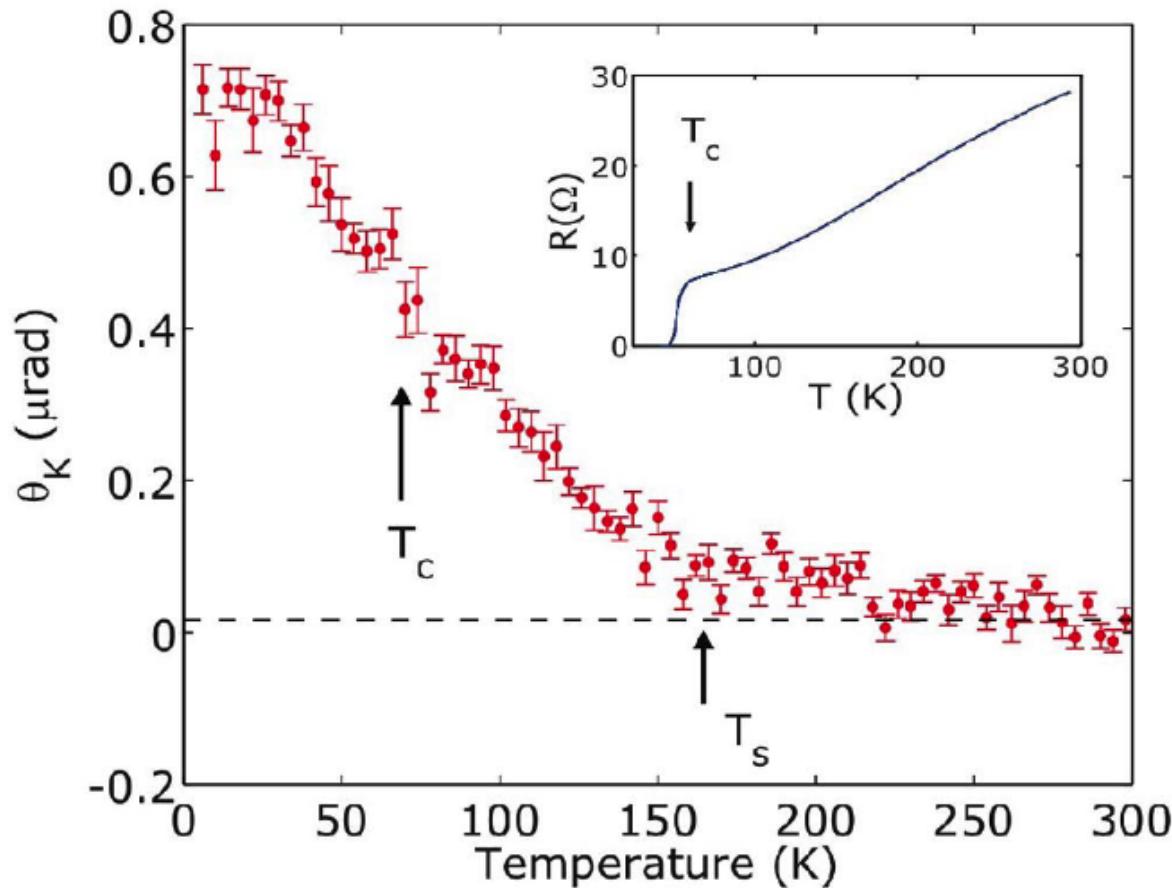


Mishra *et al*, Nat. Phys. (2014)

If the pseudogap is not due to pairing, T_c is killed for $\Delta_0, \Gamma > \sim T_{c0}$



Polar Kerr Effect seen as well (time reversal breaking?)



Chiral CDW instead?

Hosur et al, PRB (2013)

Orenstein & Moore, PRB (2013)

Xia *et al.*, PRL 2008

X-ray Optical Activity (E1-E2)

1. X-ray natural circular dichroism (XNCD)

Alagna *et al.*, PRL 1998; Goulon *et al.*, JCP 1998 (LiIO_3)
(time reversal even part of $\sigma^L - \sigma^R$)

2. Non-reciprocal x-ray linear dichroism (NRXLD)

Goulon *et al.*, PRL 2000 (V_2O_3)
(time reversal odd part of $\sigma^{90} - \sigma^0$)

3. X-ray magneto-chiral dichroism (XM χ D)

Goulon *et al.*, PRL 2002 (Cr_2O_3)
($\sigma(\mathbf{H}) - \sigma(-\mathbf{H})$)

4. X-ray non-reciprocal directional dichroism (XNDD)

Kubota *et al.*, PRL 2004 (GaFeO_3)
($\sigma^{90}(\mathbf{H}) - \sigma^{90}(-\mathbf{H})$)

5. X-ray circular intensity differential (XCID)

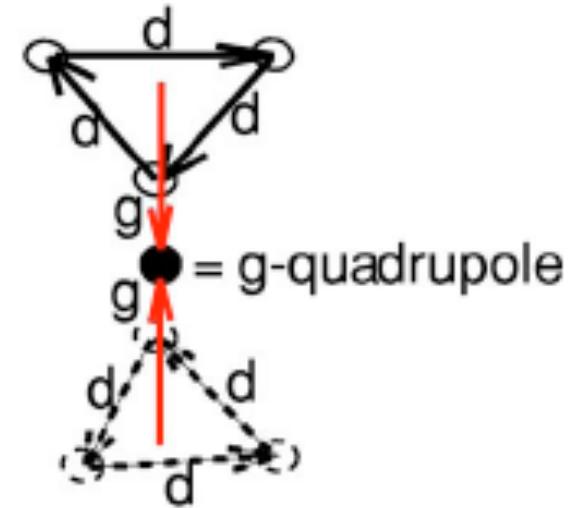
Goulon *et al.*, JPCM 2007 (ZnO)
(polar vector part of $\sigma^L - \sigma^R$)

X-ray Natural Circular Dichroism (XNCD)

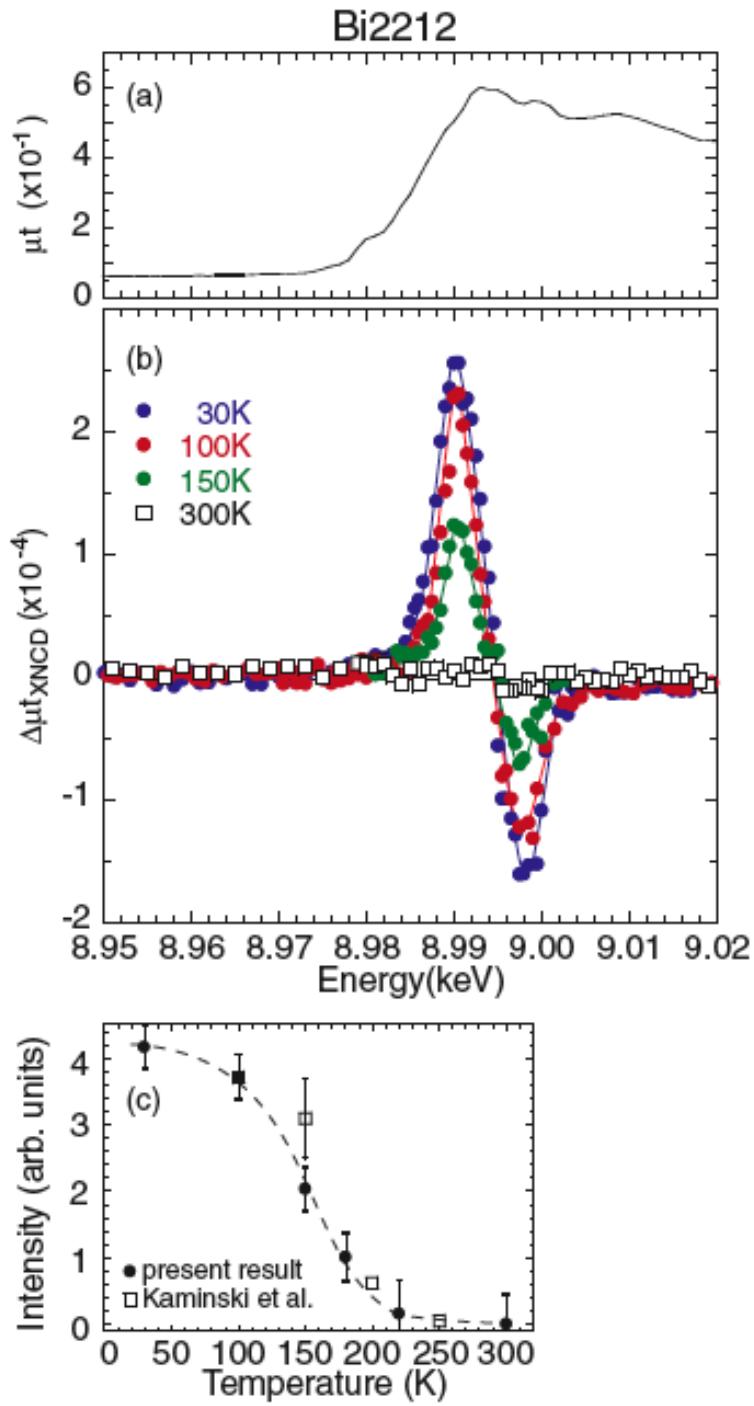
E1-E2 interference (broken inversion symmetry)

$$\vec{L} \cdot (\hat{\epsilon}^* \times \hat{\epsilon}) (\vec{\Omega} \cdot \hat{k})$$

where



- \mathbf{L} is the orbital angular momentum
- \mathbf{k} is the wavevector of the x-ray
- $\boldsymbol{\epsilon}$ is the polarization of the x-ray
- $\boldsymbol{\Omega}$ is the toroidal moment operator



XNCD
Underdoped Bi2212
($T_c = 80\text{K}$)
Cu K edge

Signal tracks ARPES dichroism

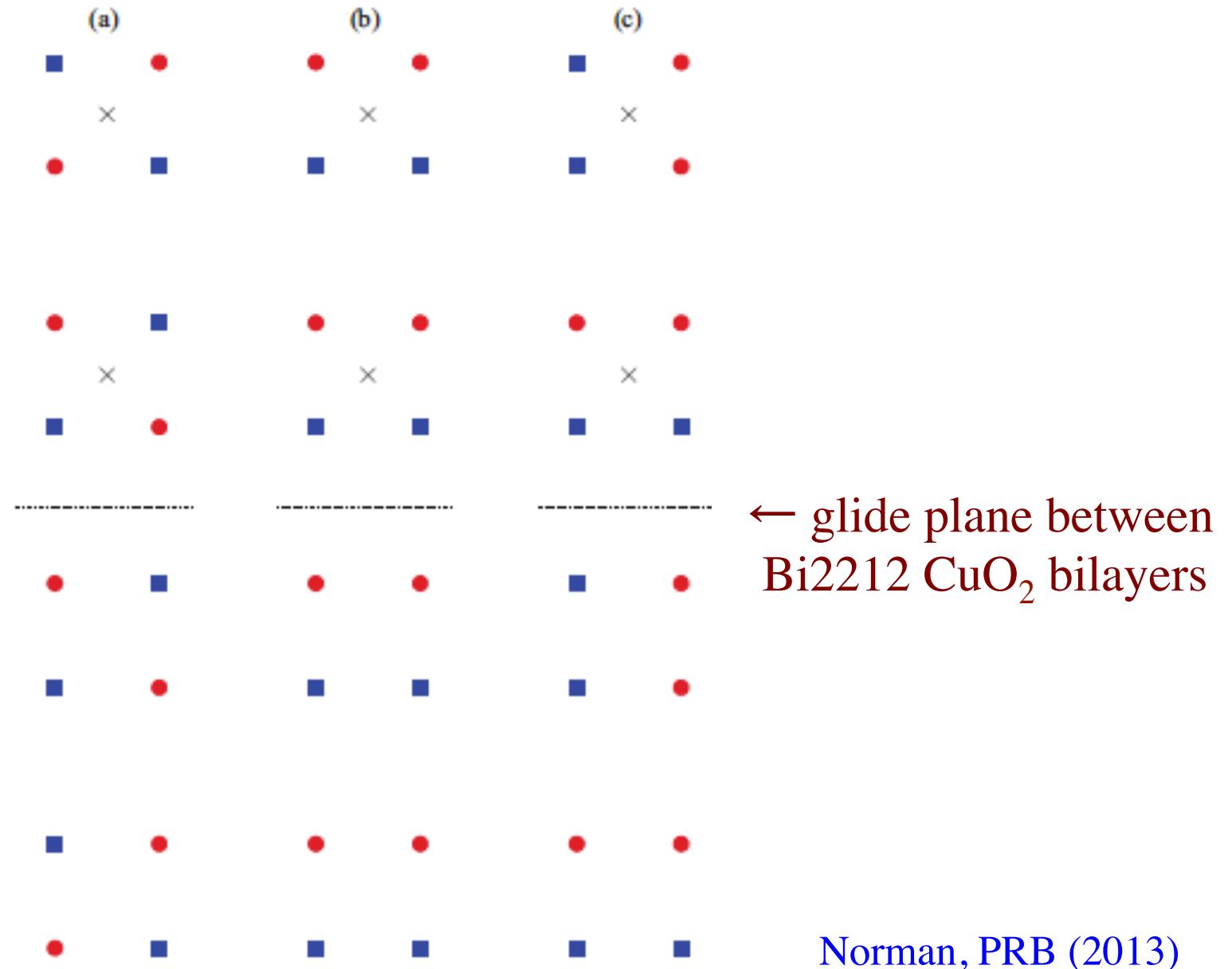
Unusual aspects

1. Simple +/- peak profile

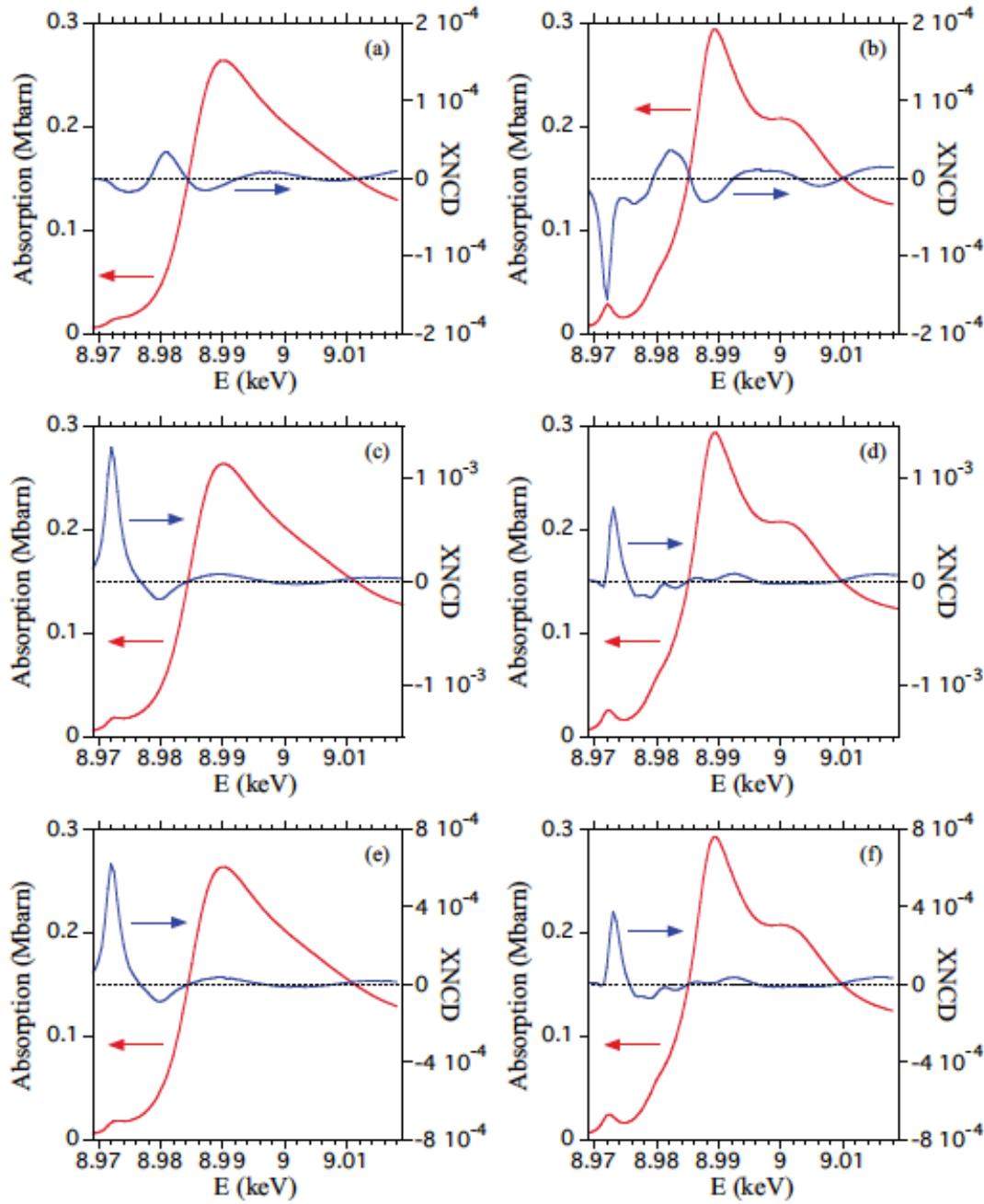
2. Peaks at edge, not pre-edge

Kubota *et al.*, JPSJ (2006)

Charge Ordering on oxygen sites (blue + vs red -)?

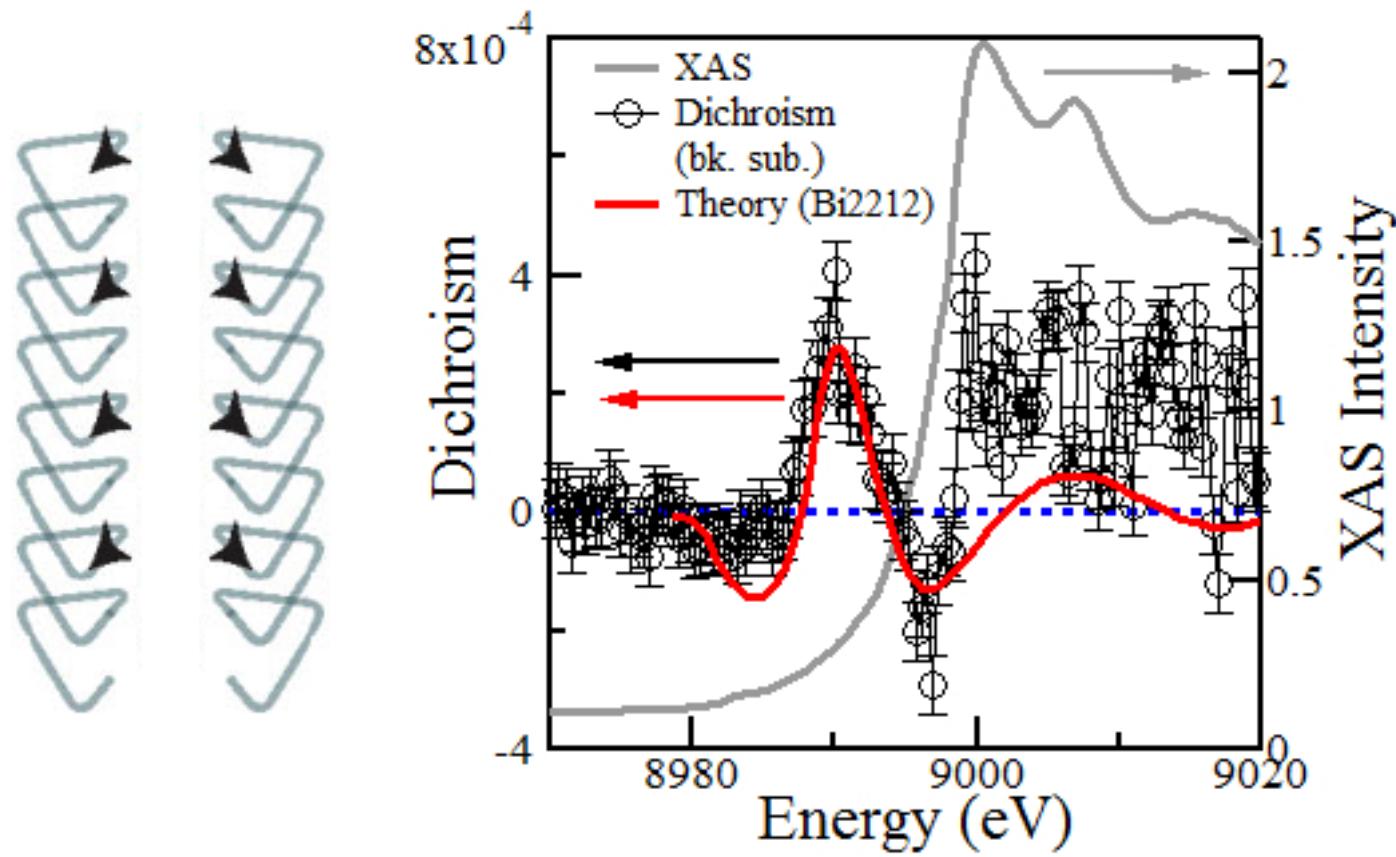


Resulting XNCD signature (Bi2212)



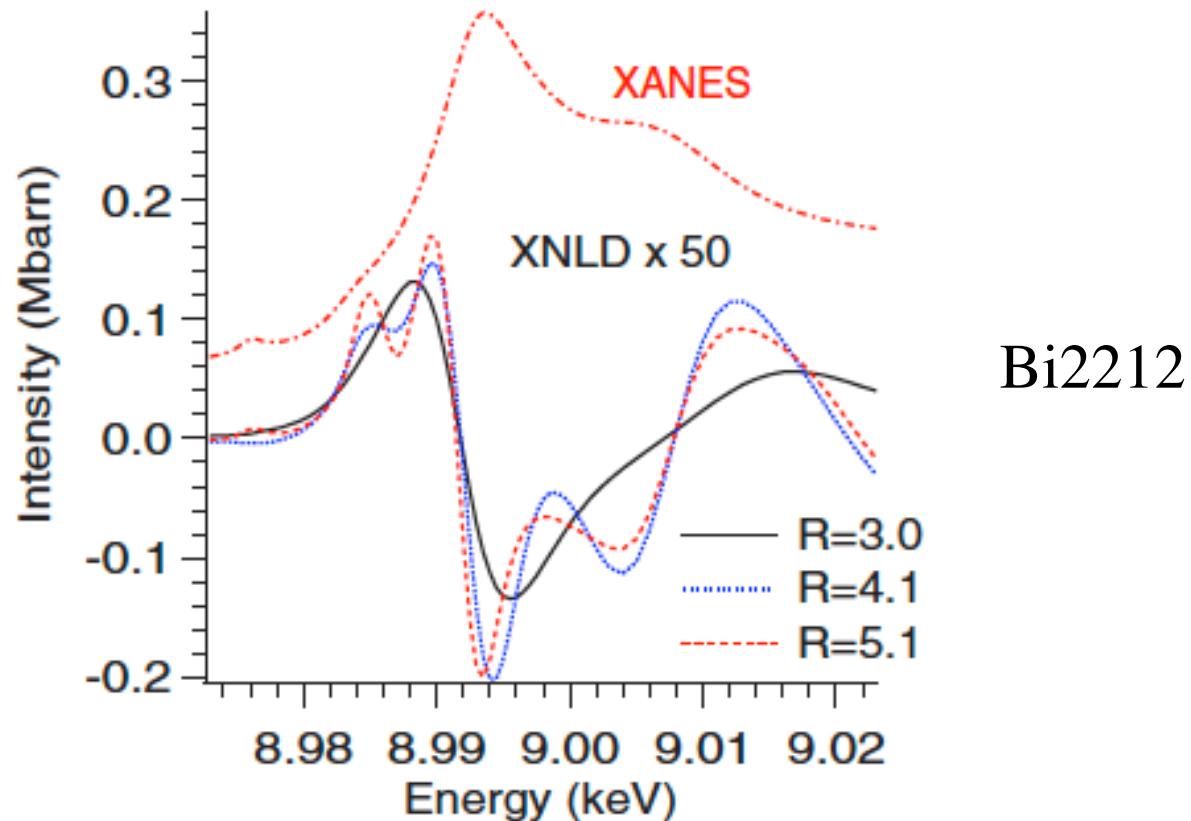
Norman, PRB (2013)

XNCD in 1/8 doped LBCO?



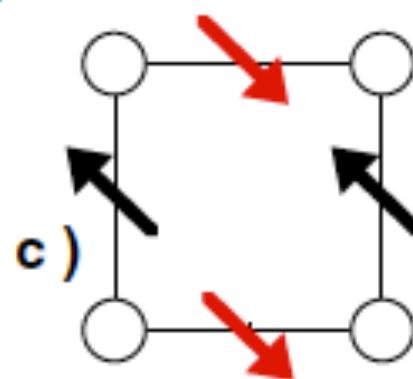
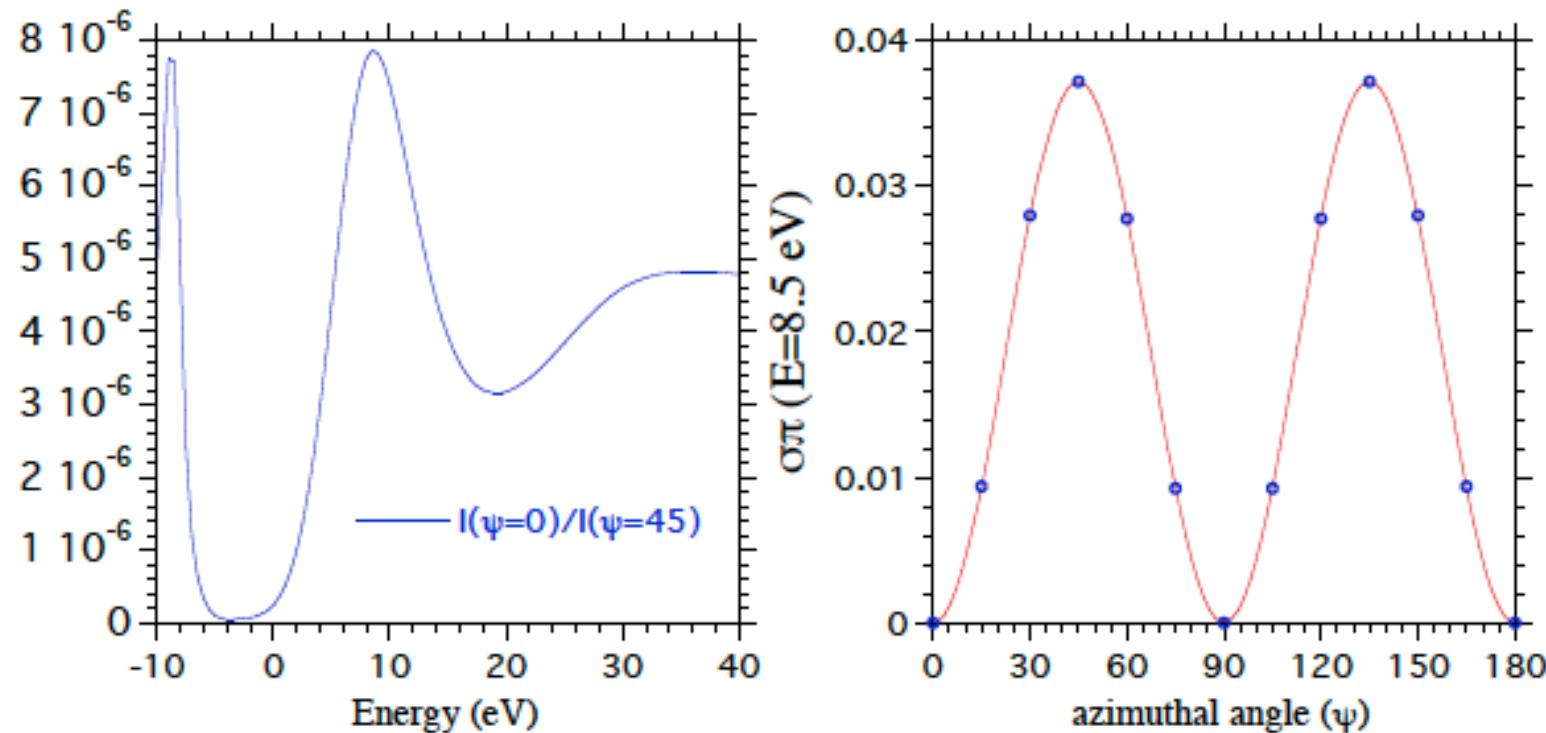
Cu K Edge XNCD Signal for LBCO
[J. He, Boston College, unpublished data]
compared to Norman (PRB, 2013) for Bi2212

Linear Dichroism Contamination?



di Matteo & Norman, PRB (2007)

Detecting Intra-unit Cell Magnetism at the Cu K edge ($\sigma\pi$ scattering completely dominated by structural contribution)



CONCLUSIONS

- CDW order appears to be a consequence of the pseudogap, not the cause
- The relation of the CDW wave vector to the Fermi surface geometry is still an unsettled matter
- The Harrison-Sebastian model for the dHvA electron pocket has a number of attractive features, but has issues as well
- The pseudogap has something to do with pairing, otherwise it is difficult to explain why T_c remains high
- X-ray dichroism & scattering are unique probes of chiral CDW order & novel time-reversal symmetry breaking states